CR 114625
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BOEING

CODE IDENT. NO. 77272

NUMBER D160-10021-1

TITLE A COMPENDIUM OF STATIC AND CRUISE TEST RESULTS FROM A SERIES OF TESTS

CR 114625
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REV LTR

THE BOEING COMPANY

VERTOL DIVISION · PHILADELPHIA, PENNSYLVANIA

CODE IDENT. NO. 77272

NUMBER D160-10021-1

TITLE A COMPENDIUM OF STATIC AND CRUISE TEST RESULTS FROM A SERIES OF TESTS ON 13 FT DIAMETER LOW DISC LOADING ROTORS

ORIGINAL RELEASE DATE ________. FOR THE RELEASE DATE OF SUBSEQUENT REVISIONS, SEE THE REVISION SHEET. FOR LIMITATIONS IMPOSED ON THE DISTRIBUTION AND USE OF INFORMATION CONTAINED IN THIS DOCUMENT, SEE THE LIMITATIONS SHEET.

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6.1-4						7.1-1					
6.1-5						7.1-2					
6.1-6						7.1-3					
6.1-7						7.1-4					
6.1-8						7.1-5					
6.1-9						7.1-6					

FORM 46284 (7/67)

ACTIVE SHEET RECORD

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7.1-8						7.3-7					
7.2						7.3-8					
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7.2-2						7.3-10					
7.2-3						8.1					
7.2-4						A-1					
7.2-5						A-2					
7.2-6						A-3					
7.2-7						A-4					
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7.2-9											
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FORM 40248 (7/67)

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FORM 46282 (2/67)

LIMITATIONS

This document is controlled by Tilt Rotor Project - Dept. 7810

All revisions to this document shall be approved by the above noted organization prior to release.

ABSTRACT

This report presents the results of a series of tests conducted on a series of 13 foot rotors with various blade twists conducted during the time period from 1969 to 1972. The tests were accomplished under a joint NASA, ONERA and Boeing agreement at AFAPL Wright Patterson Air Force Base, Ohio and the ONERA 8-meter tunnel at Modane, France. Both static and cruise performance data are presented.

SUMMARY

The series of tests were initiated to establish a data base for rotor design of low disc loading prop-rotors as applied to tilt rotor aircraft. The report presents a collection of cruise data covering the flight Mach number range of .3 to .68 on three rotors with design blade twists of 26.6°, 36° and 44°. Static hover data for 36° and 44° twist are also presented.

For the design twist of 36° both solid aluminum blades and dynamically scaled composite blades were tested to establish the effect of blade untwisting on hover and cruise performance.

The report presents data for a wide range of operating conditions, RPM, thrust, and flight Mach number to enable the user to establish the effect of propeller parameters on performance characteristics of tilt rotor aircraft.

NOTATION

C_d	Section drag coefficient
C_l	Section lift coefficient
C_T	Thrust coefficient, $T_N/\rho n^2 D^4$
C_P	Power coefficient, $P/\rho n^3 D^5$
C	Blade Chord
D	Rotor Diameter, feet
D_S	Spinner drag
FM	Propeller Figure of Merit, $0.798 \dfrac{C_T^{3/2}}{C_P}$
J	Propeller Advance Ratio, Vo/nD, with $n = \frac{rpm}{60}$
J'	$\dfrac{V_O \cos \alpha}{nD}$, with α: rotor tilt angle
M	Mach number
P	Shaft Power, FT-LB/SEC
P_b	Spinner base pressure
P_O	Free stream pressure
R	Rotor radius
$\bar{R}$	r/R, local blade station radius ratio
R_e	Reynolds number
S_b	Spinner base area
T_G	Gross thrust
T_N	Net thrust, $T_G + D_S$
V_O	Free stream velocity
V_t	Velocity at blade tip
t	Blade section thickness
α	Rotor tilt angle
$\beta_{.75}$	Rotor blade pitch angle at 3/4 R

$\Delta\beta$	Incremental blade twist angle
σ	Rotor solidity
ρ	Density
η	Blade efficienty at forward speed

NOTE: Although the data presented in this report are in conventional propeller terminology, the helicopter usage is included for the reader's convenience.

HELICOPTER ROTOR TERMINOLOGY

C_{P_h}	Power coefficient, $\frac{P}{\rho\pi R^2 V_T{}^3}$
C_{T_h}	Thrust coefficient, $\frac{T_N}{\rho\pi R^2 V_T{}^2}$
μ	Advance Ratio, V_o/V_T
$F.M._h$	Hover Figure of Merit, $.707 \frac{C_{T_h}{}^{3/2}}{C_{P_h}}$
η_h	Cruise efficiency, $\frac{\mu C_{T_h}}{C_{P_h}}$

ROTOR/PROPELLER RELATIONSHIPS

J	$= \pi\mu$
C_T	$= 7.75 C_{T_h}$
C_P	$= 24.35\ C_{P_h}$
η_h	$= \eta_h$
FM	$= FM_h$

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LIST OF FIGURES

1.0 INTRODUCTION

During the 1960-68 time period a number of companies engaged in preliminary design studies of tilt rotor aircraft. These vehicles used large diameter/low disc loading rotors which were rotated from a horizontal plane in hover to an axial position for cruise flight. At that time very little data were available to confirm the predicted performance of these rotors in hover or in cruise where speeds up to Mach=.7 were obtainable with the installed power dictated by hover requirements.

To confirm the rotor performance predictions and gain an insight into the effect of key rotor design parameters on cruise and hover performance, a test program was initiated in 1968 involving NASA-Ames, the Army AMRDL, the Boeing Vertol Company and ONERA of France. The program undertaken involved testing of five aluminum 13 foot diameter rotors designed for a range of blade twists and one torsionally dynamically scaled rotor - both static and high speed cruise testing was pursued. Total twist was varied from 26° to 44° for the rotor designs. Static tests were conducted at the Air Force test facility at Wright-Patterson AFB and NASA-Ames with cruise and transition tests completed at the NASA-Ames 40x80 and ONERA 8-meter wind tunnels. These tests were conducted in several test periods starting in 1968 and ending in 1972.

This report presents the hover and cruise test results for rotors wtih 26° "F" twist, 36° "E" twist, and 44° "D" twist. The "F" and "D" twist blades are the extremes of the twist range explored with the "E" twist being the design twist selected for a tilt rotor design study conducted by Boeing.

B

2.0 DISCUSSION

Presented in this report is a collection of all the data obtained from the cruise and hover tests conducted over a four year period. The data section is divided into two major sections, Static Performance, Section 6 and Cruise Performance, Section 7. Static performance is subdivided to present test results for D and E design twists while the cruise data presents results for D, E, and F twists. All performance coefficients presented in this document are in conventional propeller terminology.

A complete data index indicating the test ranges, in terms of operating condition and types of data presented is given in Section 5.

2.1 STATIC PERFORMANCE

Static data on the D and E twist blades is presented on pages 6.1-1 thru 6.2-19. All the data included was obtained during 1972 at Wright Patterson AFB AFAPL on test stand No.3. The section is divided into two areas, the results for the D blade and those for the E blades. All data are presented to show the effect of collective angle, RPM or tip speed on static efficiency (Figure of Merit). A consistent symbol set is used throughout the static data to identify the collective angles tested, as indicated on the Figures.

On each figure a faired line has been drawn. This fairing was obtained as follows. Initially, all the test points were plotted as CT and CP versus RPM. For both E and D twist rigid

blades a fairing of this data was made to best fit the data for both CT and CP and using these fairings Figure of Merit was calculated. For the E blades because of data scatter the basic test data was carpet plotted as a function of RPM and collective angle. These plots are Figures 6.1-1 and 6.1-2.

The results for the E blades are given in Figures 6.1-1 through 6.1-21. Open symbols are test data for the rigid aluminum blades while solid symbols are are for results from the dynamically scaled blades. The faired lines on the curves are obtained for the rigid blades. Considerable data scatter is seen at low tip Mach numbers and thrust loadings for both the rigid and dynamic blades. This scatter is due to low blade Reynolds number effect and low thrust load since it is evident in the results for both rotors.

A much more consistent set of data was obtained with the D set of blades with less data scatter occurring. However, an unusually high Figure of Merit resulted at tip Mach number of .689 (1102) RPM. At this tip speed the power coefficients shown in Figure 6.2-1 are consistent with those at other RPM. However more thrust was obtained at this condition and Figures of Merit appear to average 6 points higher than expected. This is attributed to a vibration that occurred with the test facility which induces blade oscillation and contributed dynamic lift to the blades without separation which would be

reflected in the power coefficients. Because of this, Figures 6.2-7 and 6.2-13 indicate a lower Figure of Merit based on the faired data of Figures 6.2-1 and 6.2-2 which is recommended when using the data.

2.2 CRUISE DATA

Cruise data from tests in the ONERA tunnel for F, E, and D twist blades are presented in Section 7. These results were obtained in test periods in 1969, 1970 and 1972. Data is presented at each flight Mach number condition for C_P and η as a function of advance ratio (J) and thrust coefficient (C_T). The tests were conducted over a Mach number range from .3 to .68 to cover the cruise flight envelope capability of low disc loading tilt rotors.

The technique used to obtain the data was as follows. Initially, the tunnel speed was established while the rotor speed and collective angle were advanced to maintain zero thrust. When the desired collective angle and tunnel Mach number was obtained power was increased and rotor RPM varied while collective angle was maintained until maximum thrust within the blade design operating envelope was achieved. Continuous data samples were taken with both increasing and decreasing power RPM, after an RPM power sweep had been completed to the next desired setting and the procedure repeated. Because of the continuous data sampling technique produced almost a solid line of test data and to aid in clarity of the resulting

data plots all the test points are not indicated in the figures in Section 7. The extremes of the test data are indicated on the lines of constant collective angles by circles.

Section 7 presents results of the cruise testing as C_P and η versus J for constant C_T at a constant flight Mach number. To create these plots an interpolative computer program was created. All of the test data points for a given Mach number were input to the program. The program used the input data to establish a curve fit which in turn was interpolated to obtain the C_P or η with the appropriate J for a desired C_T level on each line of collective angle.

The cruise data presented in Section 7 is subdivided into three subsections. Data for the F twist in Section 7.1, for E twist in Section 7.2 and D twist in Section 7.3

3.0 ROTOR DESIGN

All rotors tested during these programs were 3-bladed, with a 13-foot diameter. The basic design was evolved from a Boeing tilt rotor study of a medium lift helicopter replacement in the gross weight class of 40,000 to 50,000 LB. This required 55 foot diameter rotors to maintain disc loading of 10 PSF. The 13/55 scale ratio was selected to provide a Reynolds number which was acceptable for static thrust testing and a diameter which was compatible with the ONERA tunnel.

Detail taper, thickness and twist variation of the rotor as a function of percent radius are given in Figure 3.1. An alphabetical designation scheme was used to identify the design twists as given in Table 3.1. Airfoil, taper and twist distributions were not varied. Total rotor solidity (σ) was .086.

TABLE 3.1 BLADE IDENTIFICATION

DESIGNATION	TWIST
D	44° Aluminum Blades
E	36° Aluminum Blades
F	26.6° Aluminum Blades
E'	36° Dynamically Scaled Blades

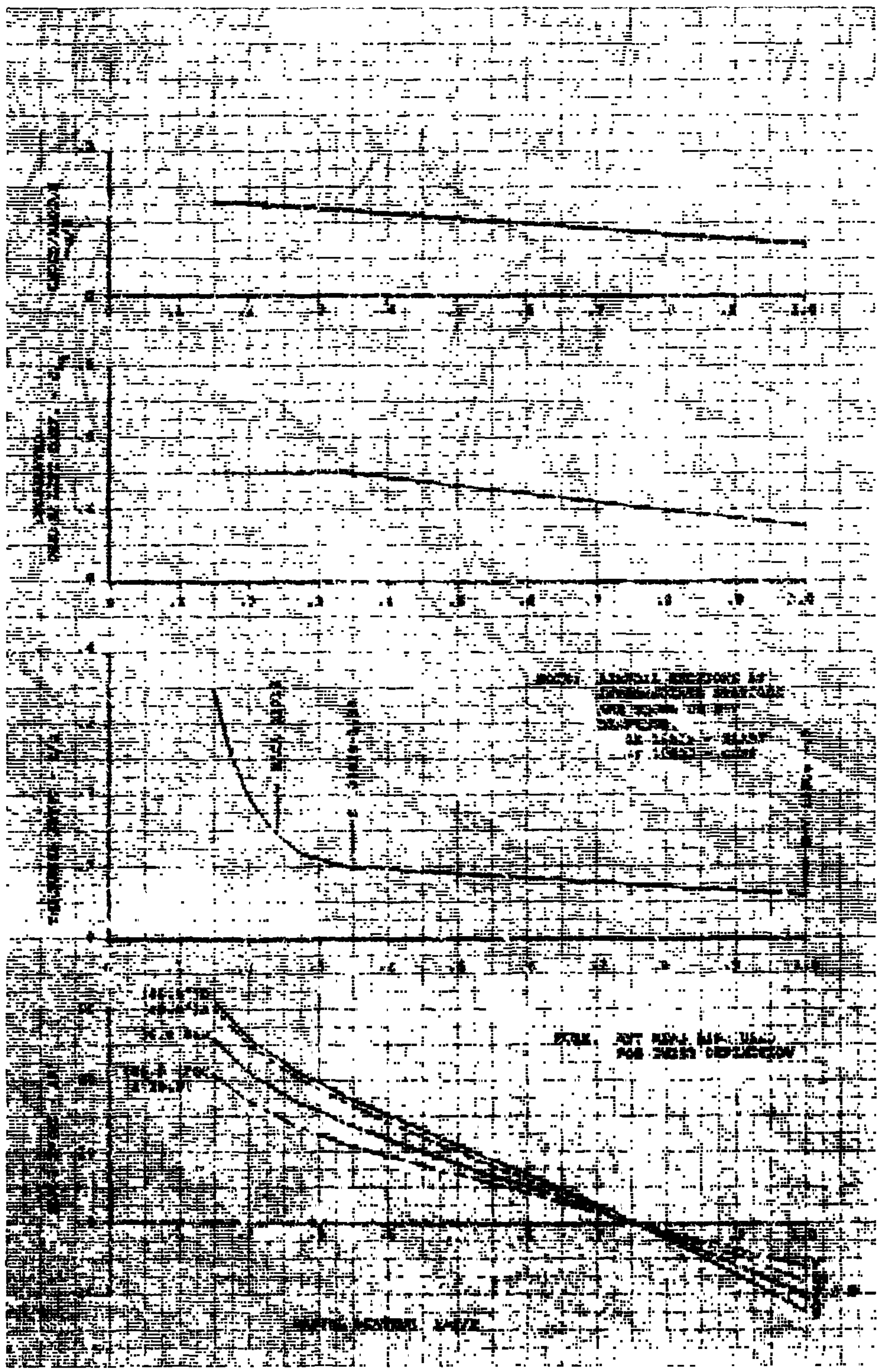


FIGURE 3.1 BLADE CHARACTERISTICS

4.0 TEST INSTALLATIONS

The static tests were performed at AFAPL Wright Patterson Air Force Base test stand No.3. The rotor was fitted to the test stand on a 13 foot extension to eliminate the blockage effect of the stand. The installation is shown in the picture, Figure 4.1 with the installation details shown in Figure 4.3. The baffle shown in Figure 4.1 was used to establish dynamic characteristics of the dynamic rotor and establish the operating envelope of the E' dynamic blades. It was removed for performance testing.

Cruise test installation at the ONERA 8-meter tunnel is shown in the picture, Figure 4.2 with the installation details shown in Figure 4.4.

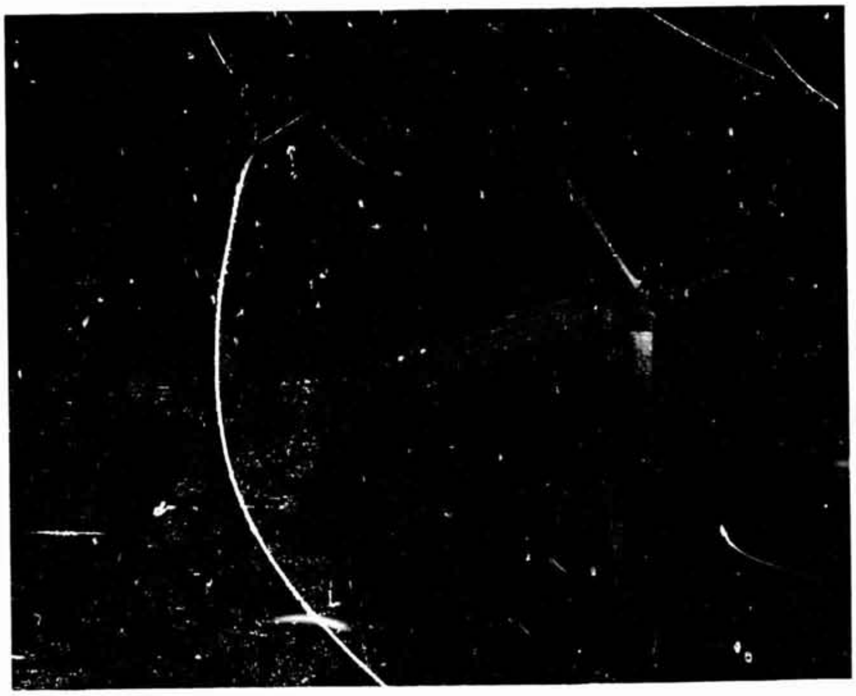


FIGURE 4.1 STATIC TEST INSTALLATION AFAPL TEST STAND 3

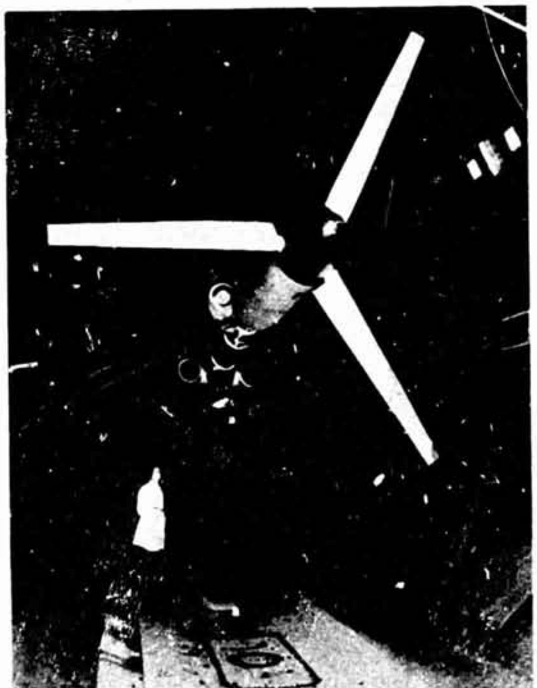


FIGURE 4.2 CRUISE TESTING INSTALLATION ONERA 8-METER TUNNEL

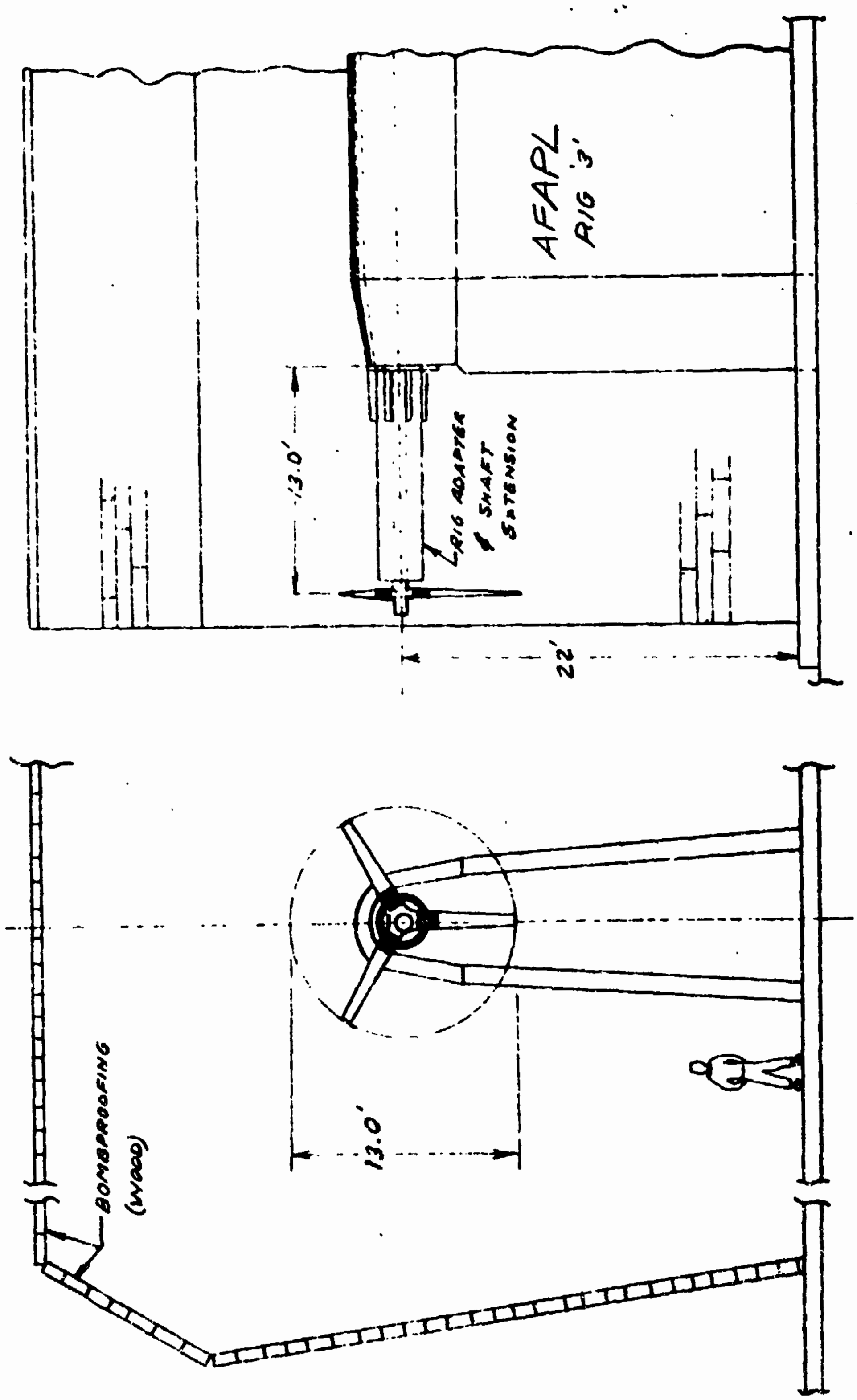


FIGURE 4.3 AFAPL RIG 3 INSTALLATION DETAILS

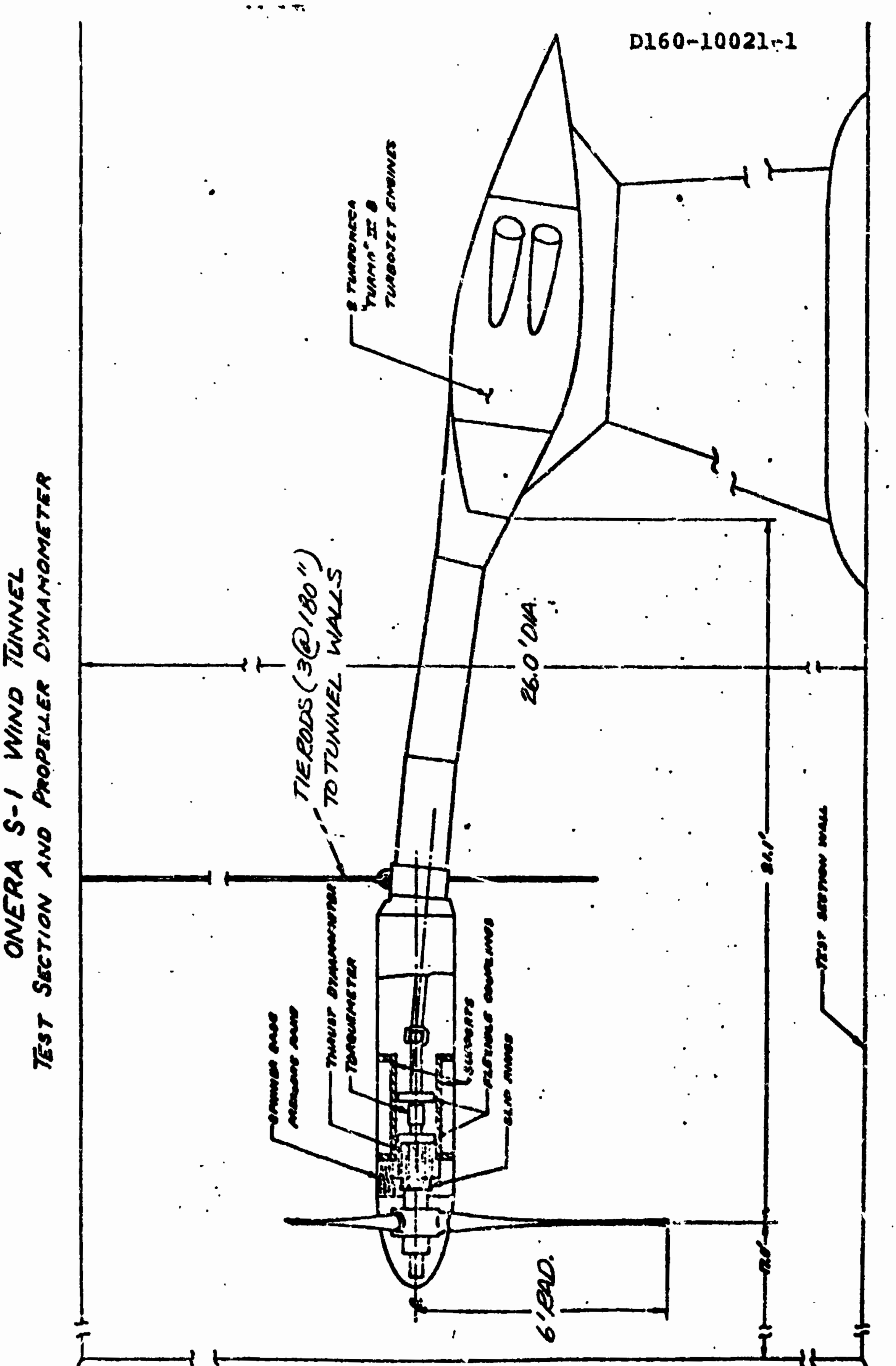


FIGURE 4.4 ONERA 8-METER TUNNEL INSTALLATION DETAILS

5.0 DATA INDEX

5.1 STATIC DATA

BLADE DESIGN	ROTOR RPM	TIP MACH NO.	COLLECTIVE RANGE	PLOT TYPE	PAGE
E	600 to 1400		2° to 16°	C_T vs RPM & θ	6.1-1
E	600 to 1400		2° to 16°	C_P vs RPM & θ	6.1-2
E, E'		.380	4° to 16°	FM vs C_P	6.1-3
E, E'		.440	4° to 13°	FM vs Cp	6.1-4
E, E'		.5	4° to 16°	FM vs Cp	6.1-5
E, E'		.596	2° to 16°	FM vs C_P	6.1-6
E, E'		.689	2° to 14°	FM vs C_P	6.1-7
E		.780	2° to 12°	FM vs C_P	6.1-8
E		.875	2° to 12°	FM vs C_P	6.1-9
E, E'		.380	4° to 16°	FM vs C_T	6.1-10
E, E'		.440	4° to 13°	FM vs C_T	6.1-11
E, E'		.500	4° to 16°	FM vs C_T	6.1-12
E, E'		.596	2° to 16°	FM vs C_T	6.1-13
E, E'		.689	2° to 14°	FM vs C_T	6.1-14
E		.780	2° to 12°	FM vs C_T	6.1-15
E		.875	2° to 12°	FM vs C_T	6.1-16
E	900 to 1400		2°	FM vs RPM	6.1-17
E, E'	600 to 1400		4°	FM vs RPM	6.1-17
E, E'	600 to 1400		6°	FM vs RPM	6.1-18
E, E'	600 to 1400		7°	FM vs RPM	6.1-18
E, E'	600 to 1400		8°	FM vs RPM	6.1-19
E, E'	600 to 1400		10°	FM vs RPM	6.1-19

BLADE DESIGN	ROTOR RPM	TIP MACH NO.	COLLECTIVE RANGE	PLOT TYPE	PAGE
E, E'	600 to 1100		12°	FM vs RPM	6.1-20
E, E'	600 to 1100		14°	FM vs RPM	6.1-20
E, E'	600 to 800		15°	FM vs RPM	6.1-21
D	800 to 1400		8° to 16°	C_P vs RPM	6.2-1
D	800 to 1400		8° to 16°	C_T vs RPM	6.2-2
D		.5	8° to 16°	FM vs C_P	6.2-3
D		.596	8° to 16°	FM vs C_P	6.2-4
D		.367	8° to 14°	FM vs C_P	6.2-5
D		.676	8° to 14°	FM vs C_P	6.2-6
D		.689	8° to 14°	FM vs C_P	6.2-7
D		.722	8° to 14°	FM vs C_P	6.2-8
D		.737	8° to 14°	FM vs C_P	6.2-9
D		.780	8° to 14°	FM vs C_P	6.2-10
D		.87	8° to 12°	FM vs C_P	6.2-11
D		.50	8° to 16°	FM vs C_T	6.2-12
D		.596	8° to 16°	FM vs C_T	6.2-12
D		.638	8° to 14°	FM vs C_T	6.2-13
D		.69	8° to 14°	FM vs C_T	6.2-13
D		.72	8° to 14°	FM vs C_T	6.2-14
D		.79	8° to 14°	FM vs C_T	6.2-14
D		.74	8° to 14°	FM vs C_T	6.2-15
D	800 to 1400		8°	FM vs RPM	6.2-16
D	800 to 1400		10°	FM vs RPM	6.2-16
D	800 to 1400		11°	FM vs RPM	6.2-17

5.1 STATIC DATA (continued)

BLADE DESIGN	ROTOR RPM	TIP MACH NO.	COLLECTIVE RANGE	PLOT TYPE	PAGE
D	800 to 1400		12°	FM vs RPM	6.2-17
D	1000 to 1300		13°	FM vs RPM	6.2-18
D	800 to 1300		14°	FM vs RPM	6.2-18
D	800 to 1100		15°	FM vs RPM	6.2-19
D	800 to 1000		16°	FM vs RPM	6.2-19

5.2 CRUISE DATA

BLADE DESIGN	TUNNEL MACH NO.	COLLECTIVE RANGE DEG	PLOT TYPE		PAGE
			C_P, C_T, J	η, C_T, J	
F	.456	45° to 55°	x		7.1-1
F	.456	45° to 55°		x	7.1-2
F	.578	50° to 60°	x		7.1-3
F	.578	50° to 60°		x	7.1-4
F	.610	50° to 62.6°	x		7.1-5
F	.610	50° to 62.6°		x	7.1-6
F	.685	55° to 67.2°	x		7.1-7
F	.685	55° to 67.2°		x	7.1-8
1970 E' DYNAMIC	.307	40° to 47°	x		7.2-1
E' DYNAMIC	.307	40° to 47°		x	7.2-2
E' DYNAMIC	.455	50° to 54.7°	x		7.2-3
E'DYNAMIC	.455	50° to 54.7°		x	7.2-4
E' DYNAMIC	.578	57.5° to 60°	x		7.2-5
E' DYNAMIC	.578	57.5° to 60°		x	7.2-6
E'DYNAMIC	.600	57.3° to 62.2°	x		7.2-7
E'DYNAMIC	.600	57.3° to 62.2°		x	7.2-8

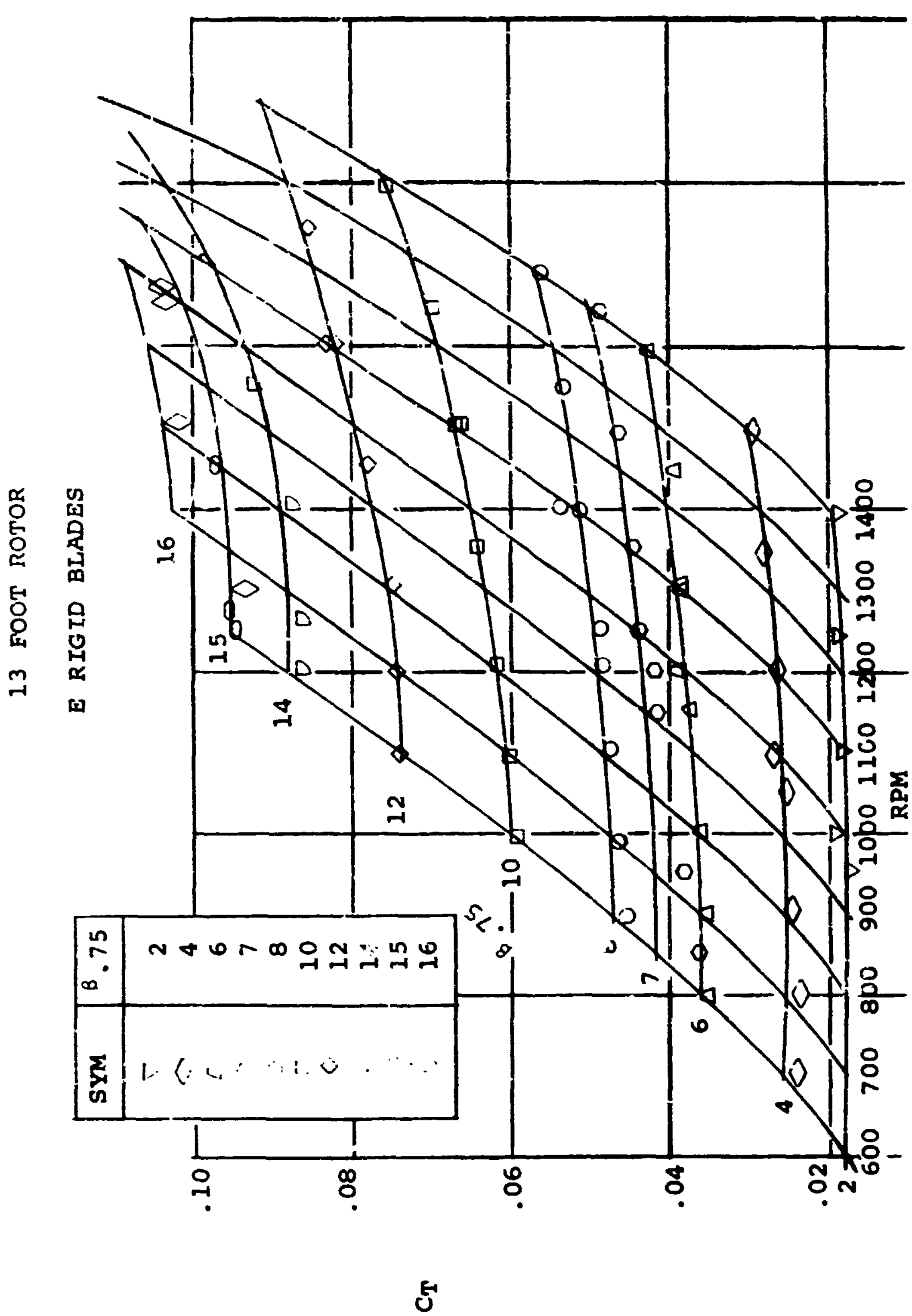
BLADE DESIGN	TUNNEL MACH NO.	COLLECTIVE RANGE DEG	PLOT TYPE C_P, C_T, J	PLOT TYPE η, C_T, J	PAGE
E' DYNAMIC	.601	57.3° to 62.2°	x		7.2-9
E' DYNAMIC	.601	57.3° to 62.2°		x	7.2-10
1972					
E' DYNAMIC	.455	50° to 57.5°	x		7.2-11
E' DYNAMIC	.455	50° to 57.5°		x	7.2-12
E' DYNAMIC	.540	55° to 62.5°	x		7.2-13
E' DYNAMIC	.540	55° to 62.5°		x	7.2-14
E' DYNAMIC	.606	60° to 64°	x		7.2-15
E' DYNAMIC	.606	60° to 64°		x	7.2-16
E' DYNAMIC	.62	61° to 64°	x		7.2-17
E' DYNAMIC	.62	61° to 64°		x	7.2-18
E 1972	.455	50° to 55°	x		7.2-19
E 1972	.455	50° to 55°		x	7.2-20
E 1972	.54	52.5° to 61°	x		7.2-21
E 1972	.54	52.5° to 61°		x	7.2-22
E 1969	.606	50° to 62.5°	x		7.2-23
E 1969	.606	50° to 62.5°		x	7.2-24
E 1972	.606	57.5° to 64.0°	x		7.2-25
E 1972	.606	57.5° to 64.0°		x	7.2-26
E 1969	.681	55° to 65.6°	x		7.2-27
E 1969	.681	55° to 65.7°		x	7.2-28
E 1972	.68	60° to 65°	x		7.2-29
E 1972	.68	60° to 65°		x	7.2-30

5.2 CRUISE DATA (continued)

BLADE DESIGN	TUNNEL MACH NO.	COLLECTIVE RANGE DEG	PLOT TYPE		PAGE
			C_P, C_T, J	η, C_T, J	
D	.457	45° to 55°	x		7.3-1
D	.457	45° to 55°		x	7.3-2
D	.578	57.6° and 60°	x		7.3-3
D	.578	57.6° and 60°		x	7.3-4
D	.582	50° to 60°	x		7.3-5
D	.582	50° to 60°		x	7.3-6
D	.609	50° to 62.6°	x		7.3-7
D	.609	50° to 62.6°		x	7.3-8
D	.681	57.5° to 67.7°	x		7.3-9
D	.681	57.5° to 67.7°		x	7.3-10

6.0 STATIC DATA

6.1 E BLADE STATIC DATA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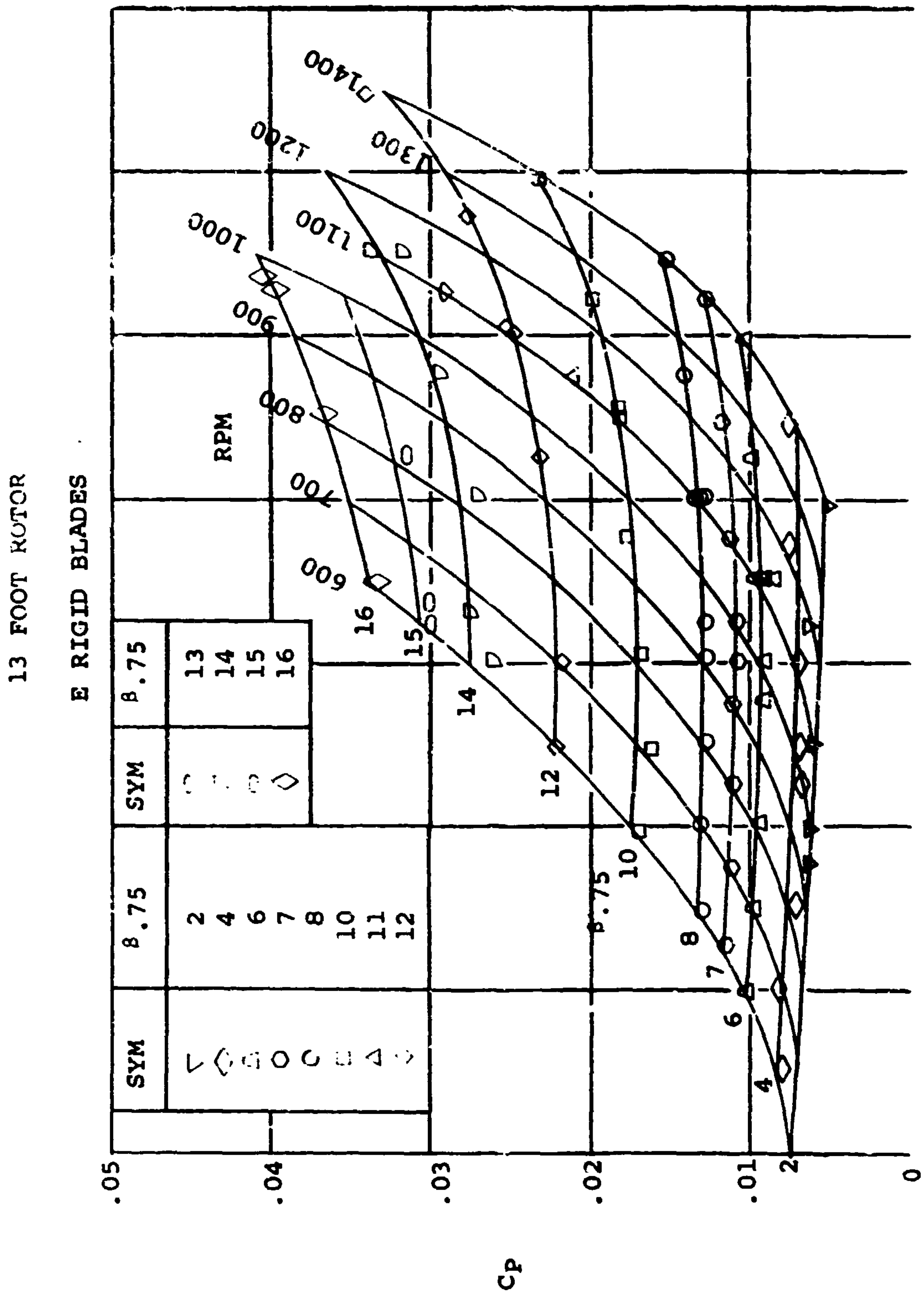
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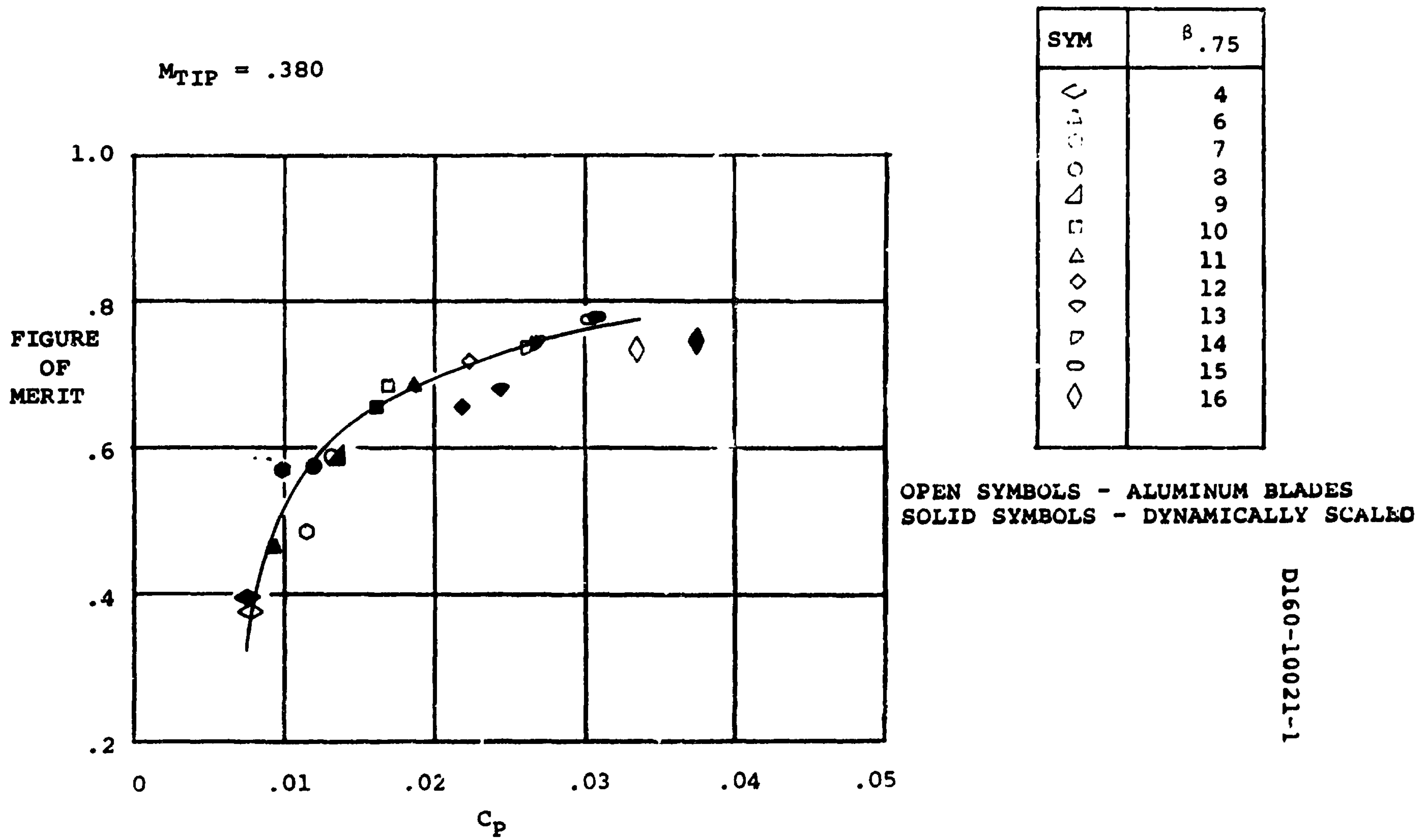
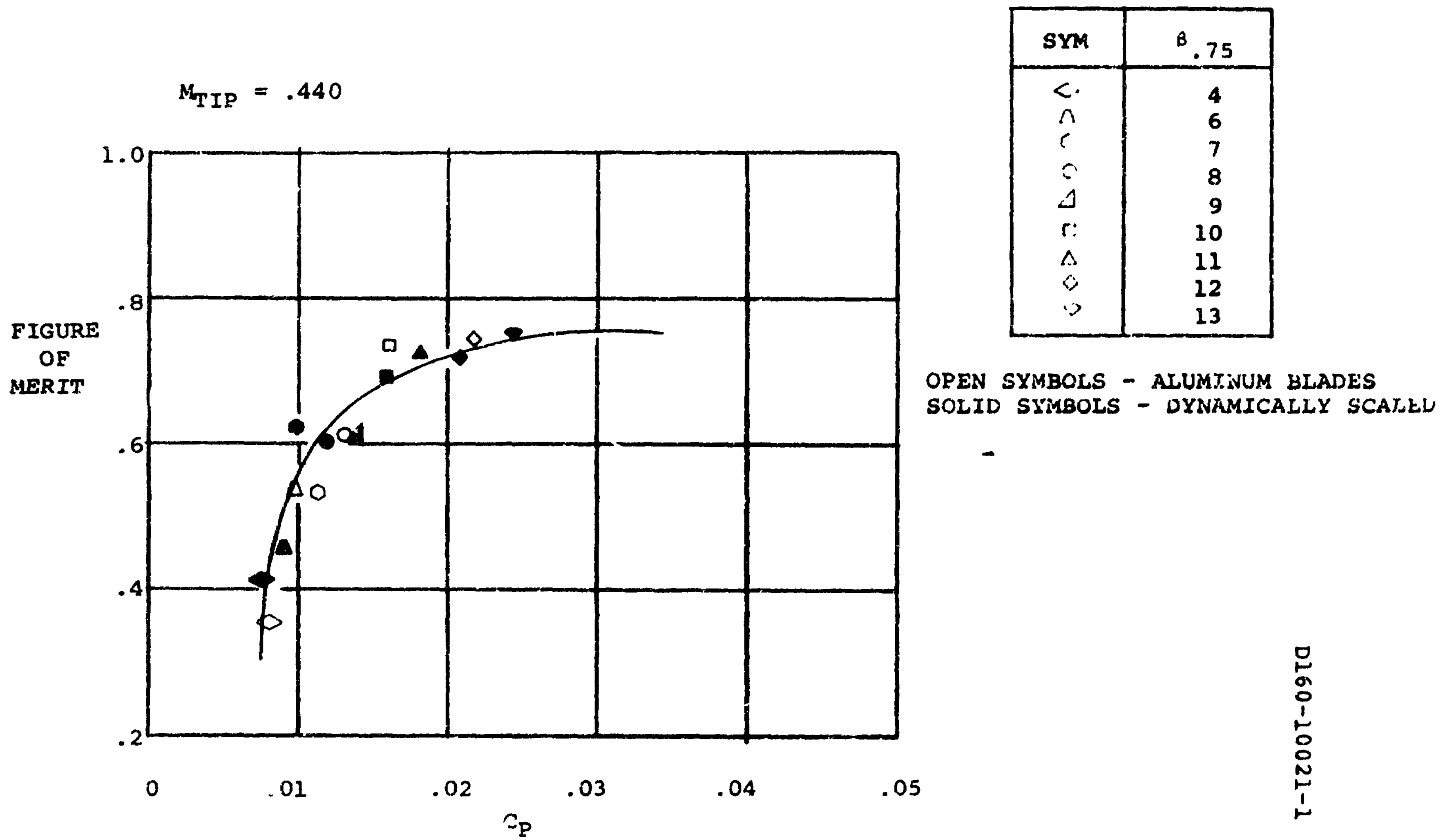
13 FOOT ROTOR

E RIGID BLADES



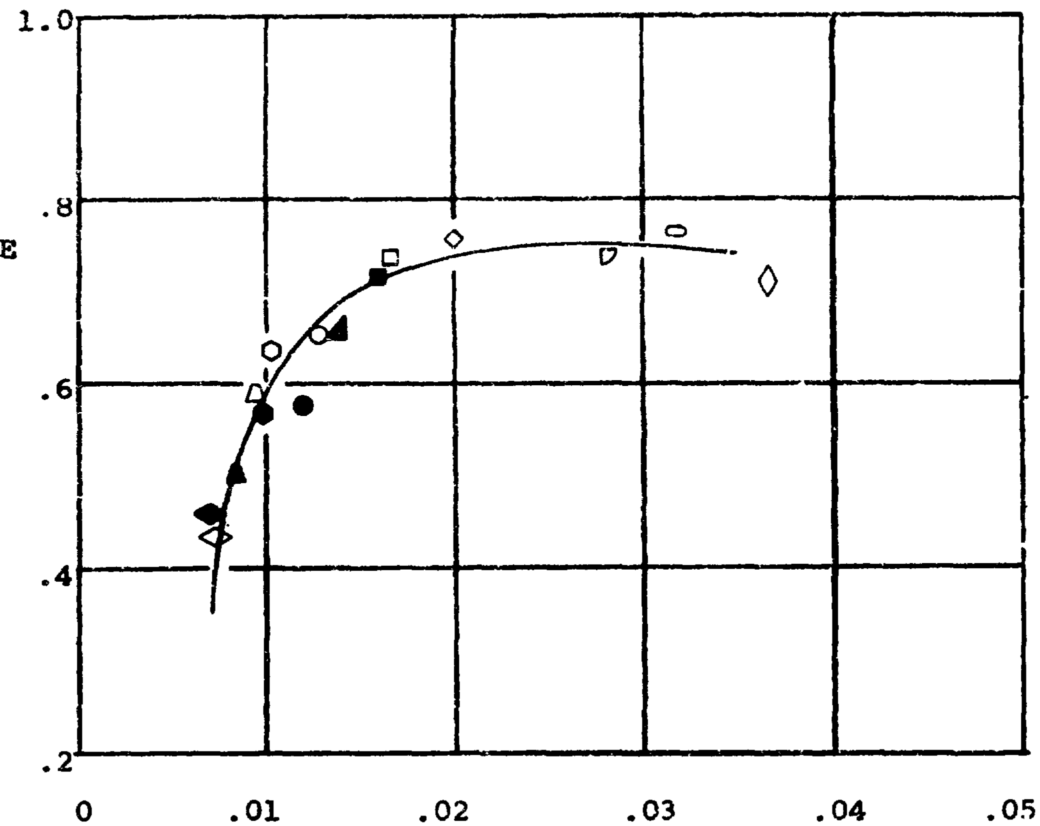
13 FOOT ROTOR

E RIGID BLADES



13 FOOT ROTOR

E RIGID BLADES

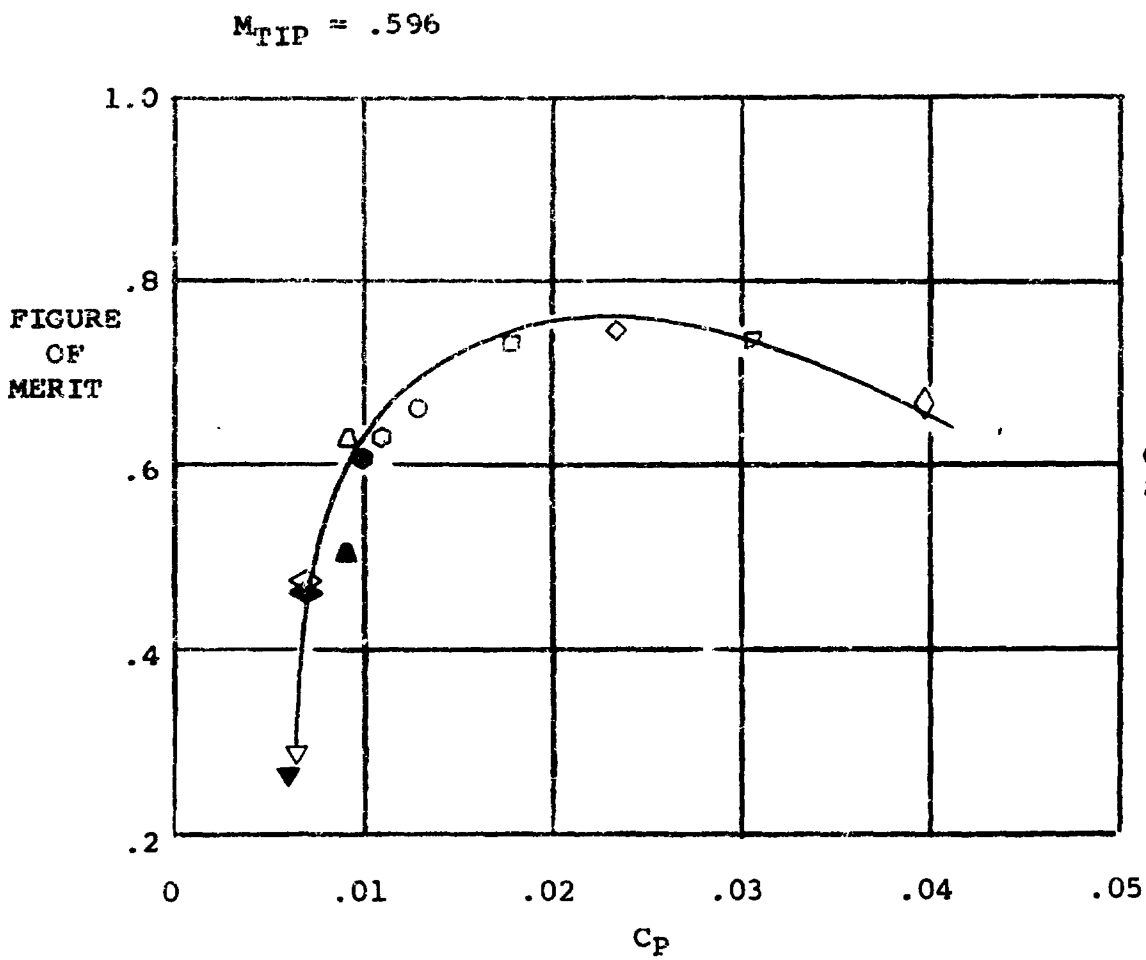


SYM	$\beta_{.75}$
◇	4
⌒	6
⬡	7
○	8
△	9
□	10
◁	12
▽	14
⌓	15
◇	16

OPEN SYMBOLS - ALUMINUM BLADES
SOLID SYMBOLS - DYNAMICALLY SCALED

13 FOOT ROTOR

E RIGID BLADES

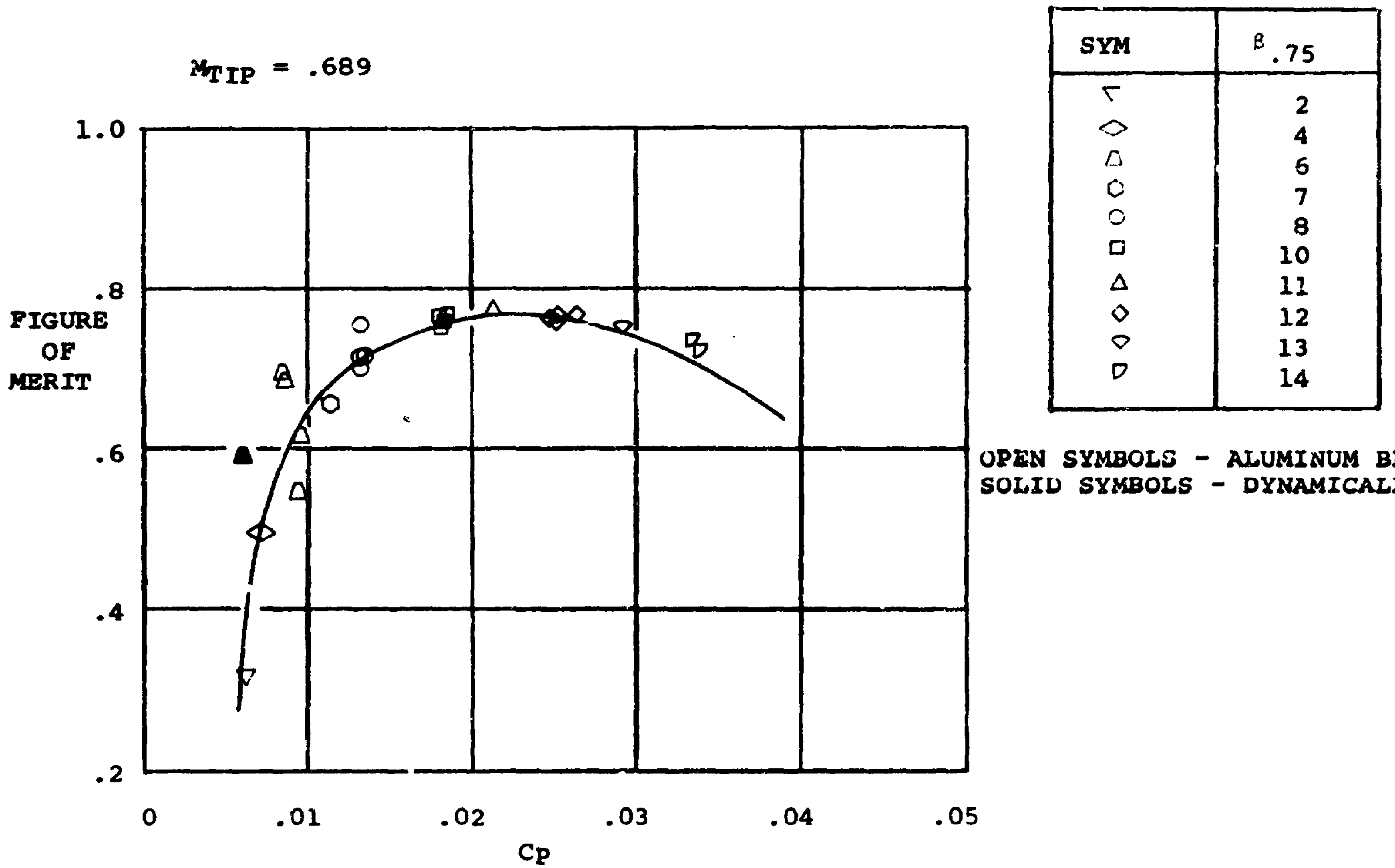


SYM	$\beta_{.75}$
▽	2
◇	4
△	6
○	7
○	8
□	10
◇	12
▷	14
◇	16

OPEN SYMBOLS - ALUMINUM BLADES
SOLID SYMBOLS - DYNAMICALLY SCALED

13 FOOT ROTOR

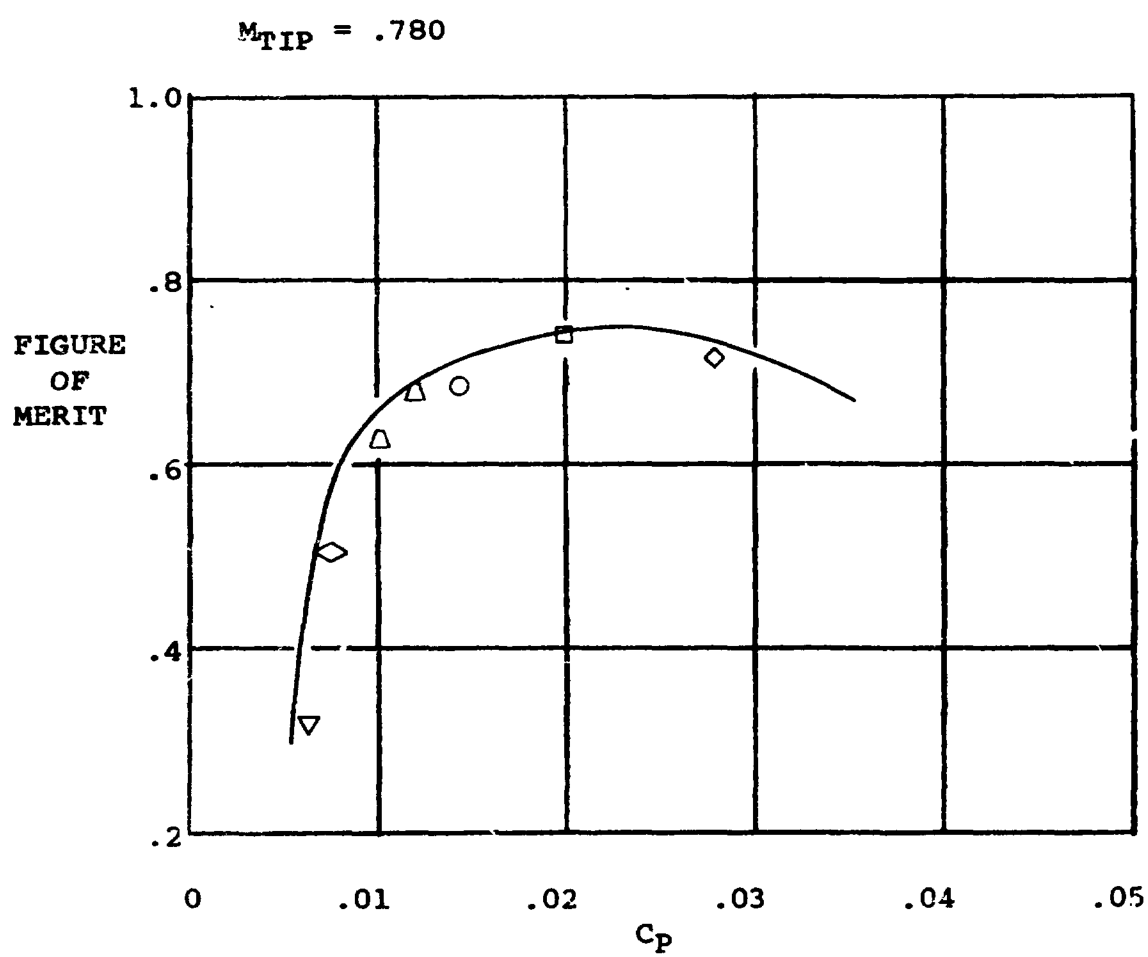
E RIGID BLADES



OPEN SYMBOLS - ALUMINUM BLADES
SOLID SYMBOLS - DYNAMICALLY SCALED

13 FOOT ROTOR

E RIGID BLADES

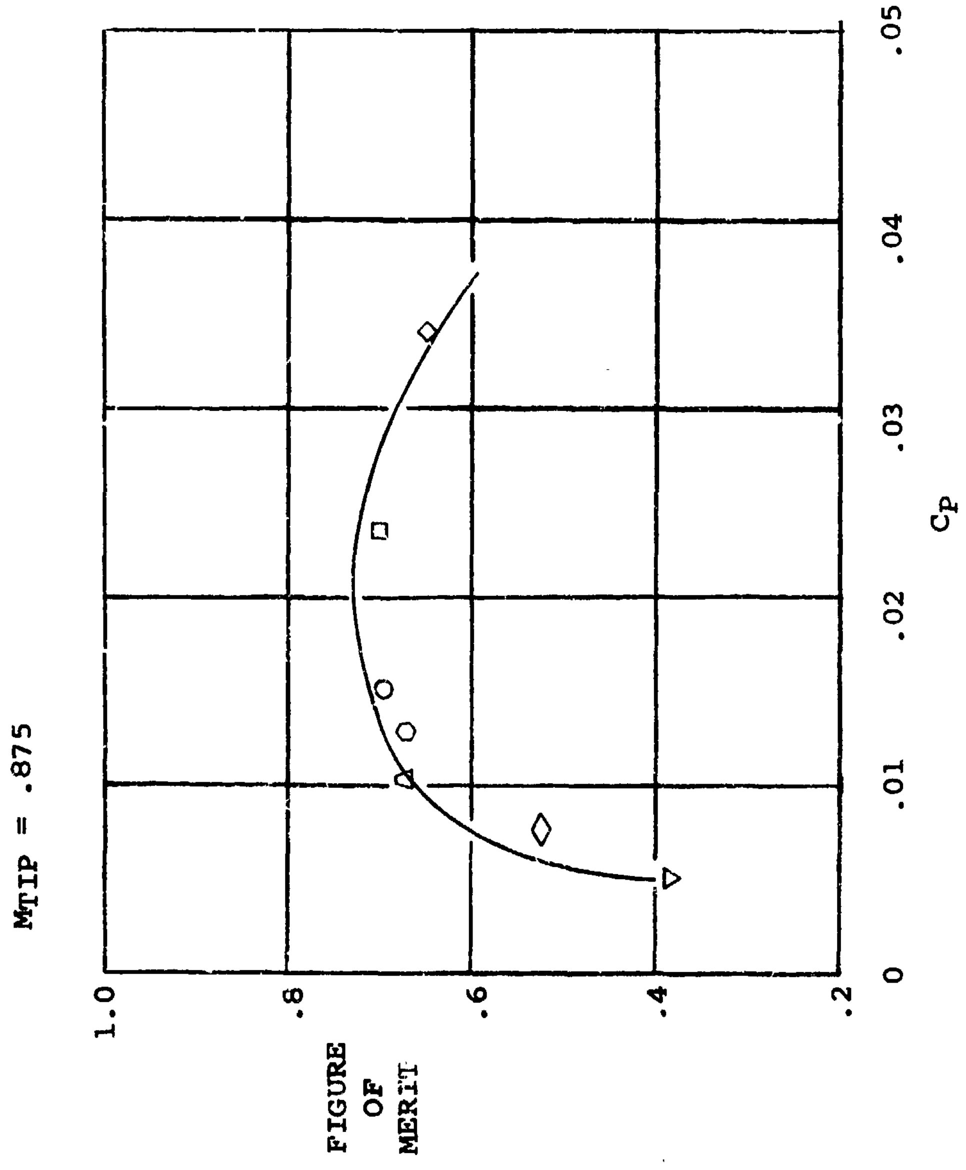


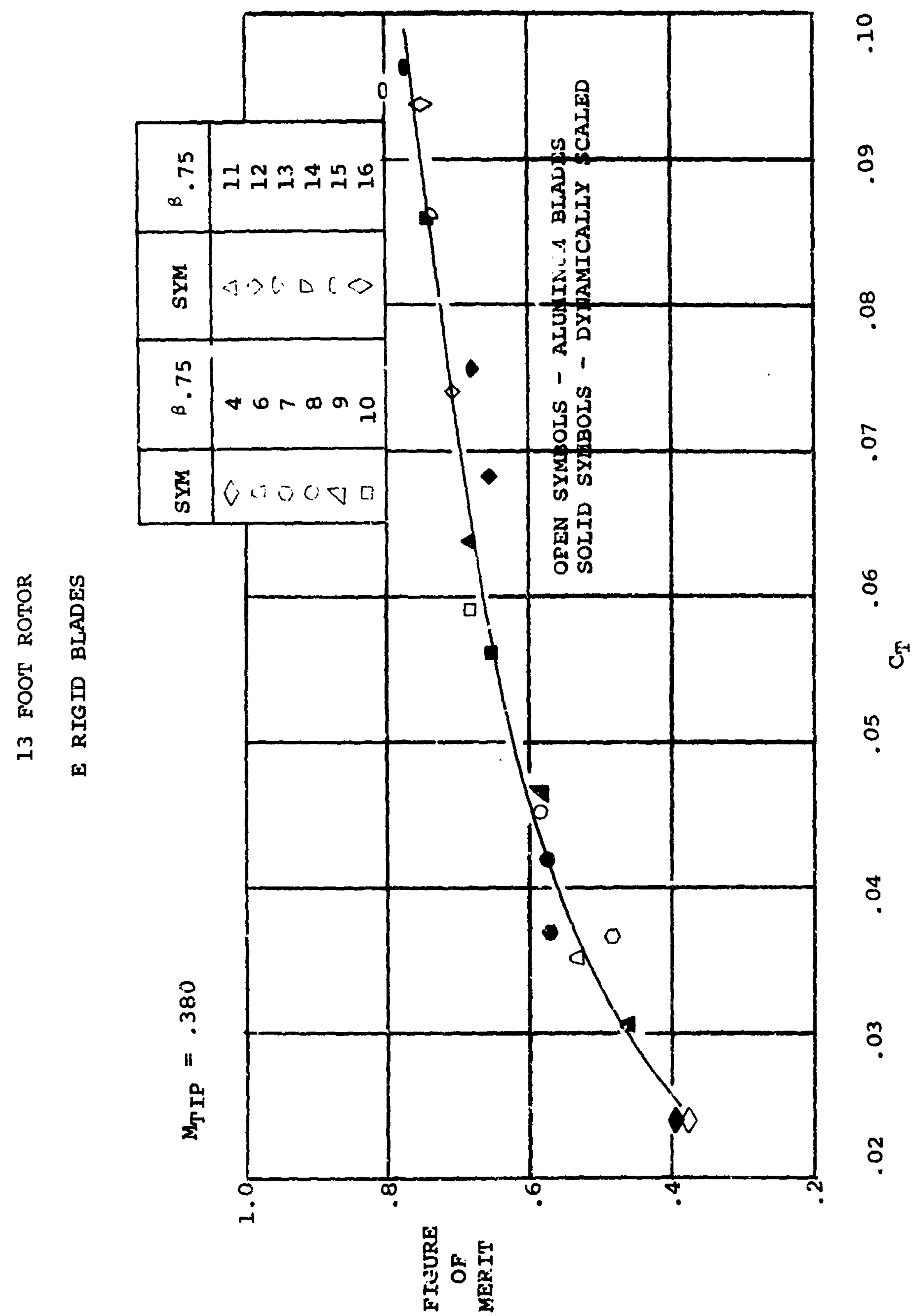
SYM	$\beta_{.75}$
◁	2
◇	4
△	6
○	8
□	10
◇	12

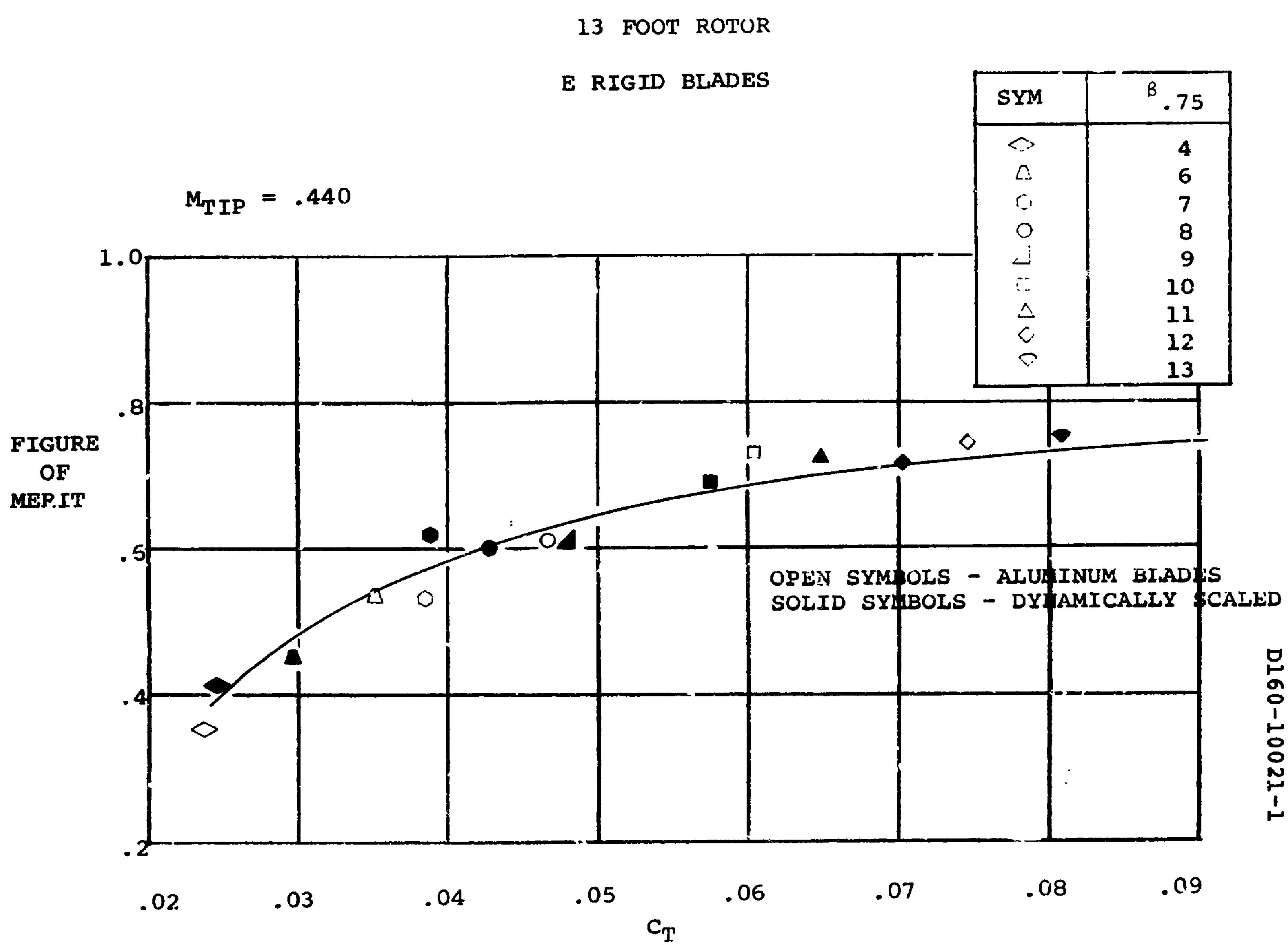
13 FOOT ROTOR

E RIGID BLADES

SYM	$\beta_{.75}$
▷	2
◇	4
◁	6
○	7
○	8
□	10
◇	12



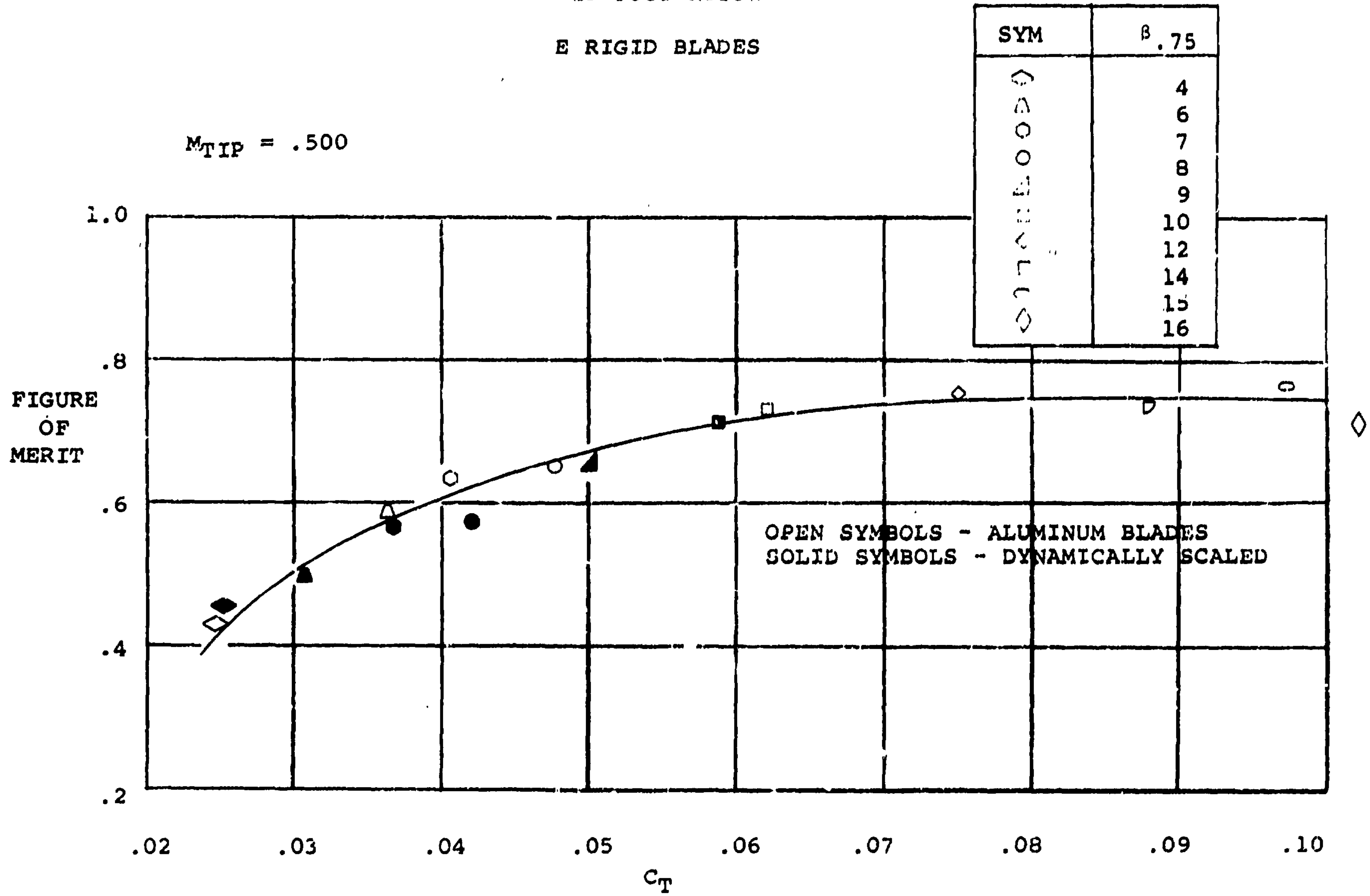

13 FOOT ROTOR
E RIGID BLADES
M_{TIP} = .380
SYM
$\beta_{.75}$
4
6
7
8
9
10
11
12
13
14
15
16
OPEN SYMBOLS - ALUMINUM BLADES
SOLID SYMBOLS - DYNAMICALLY SCALED
FIGURE OF MERIT
1.0
.8
.6
.4
.2
C_T
.02
.03
.04
.05
.06
.07
.08
.09
.10

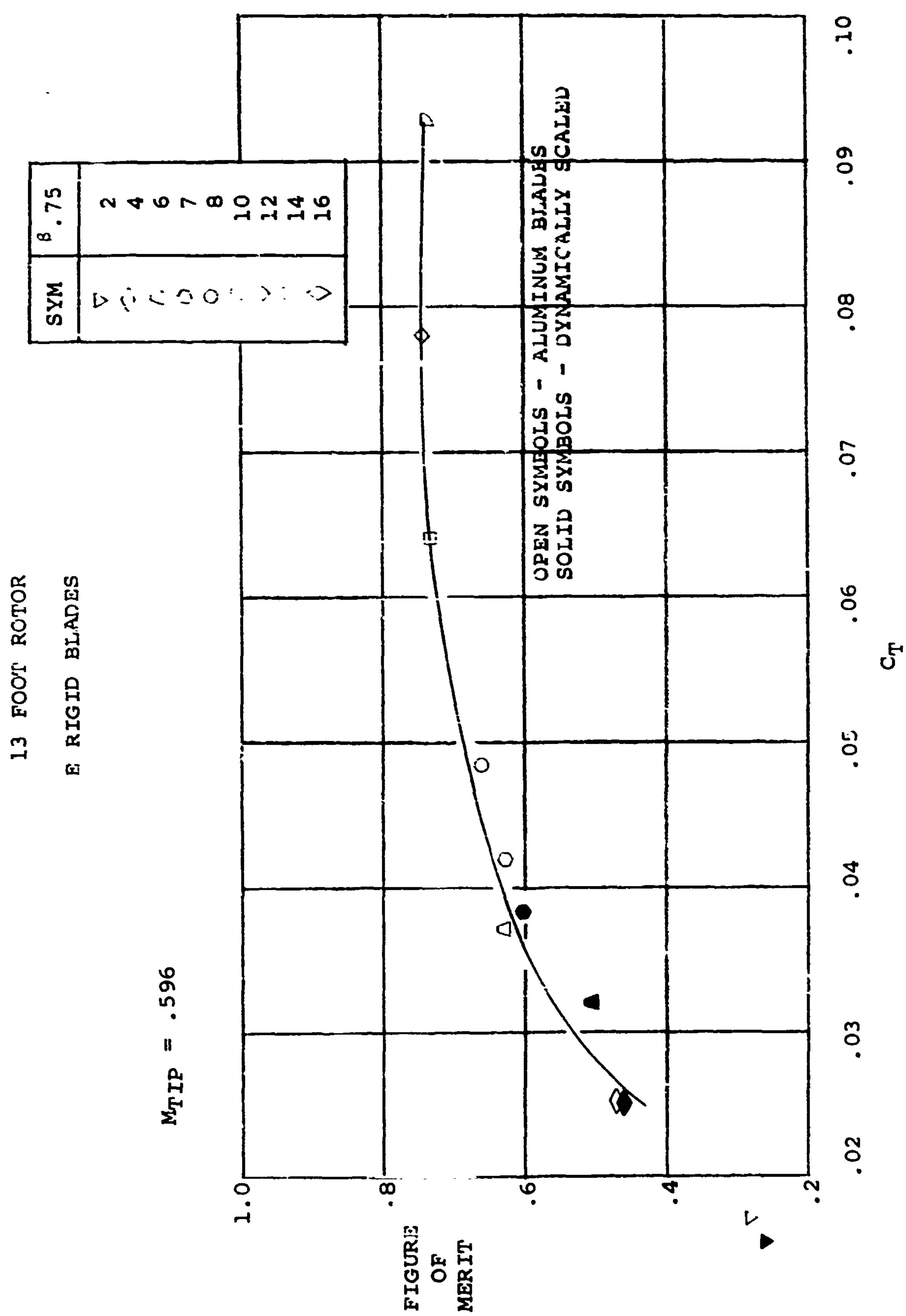

13 FOOT ROTOR
E RIGID BLADES
M_{TIP} = .440
SYM
$\beta_{.75}$
4
6
7
8
9
10
11
12
13
FIGURE OF MERIT
1.0
.8
.6
.4
.2
.02
.03
.04
.05
.06
.07
.08
.09
C_T
OPEN SYMBOLS - ALUMINUM BLADES
SOLID SYMBOLS - DYNAMICALLY SCALED

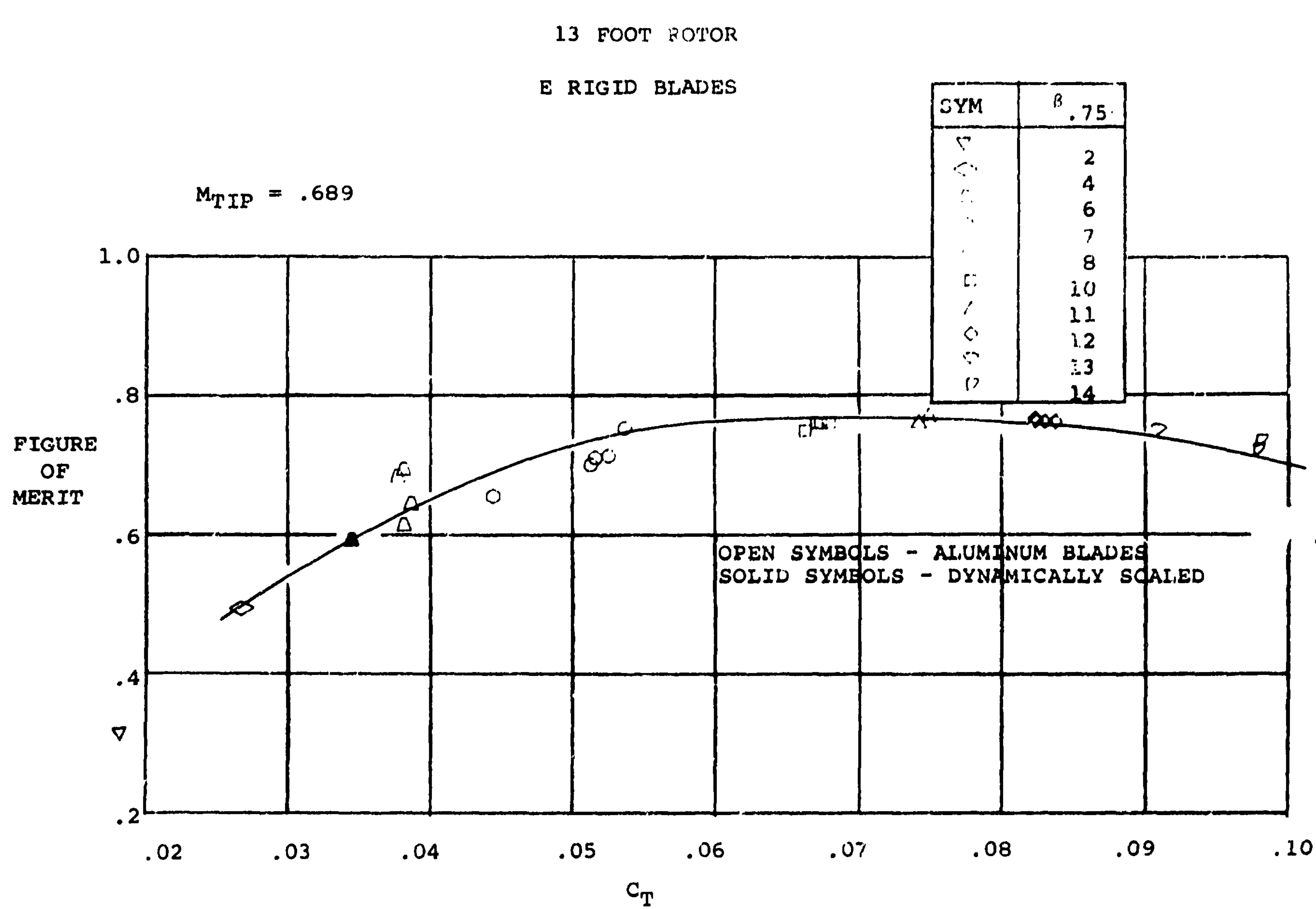
D160-10021-1

13 FOOT ROTOR

E RIGID BLADES

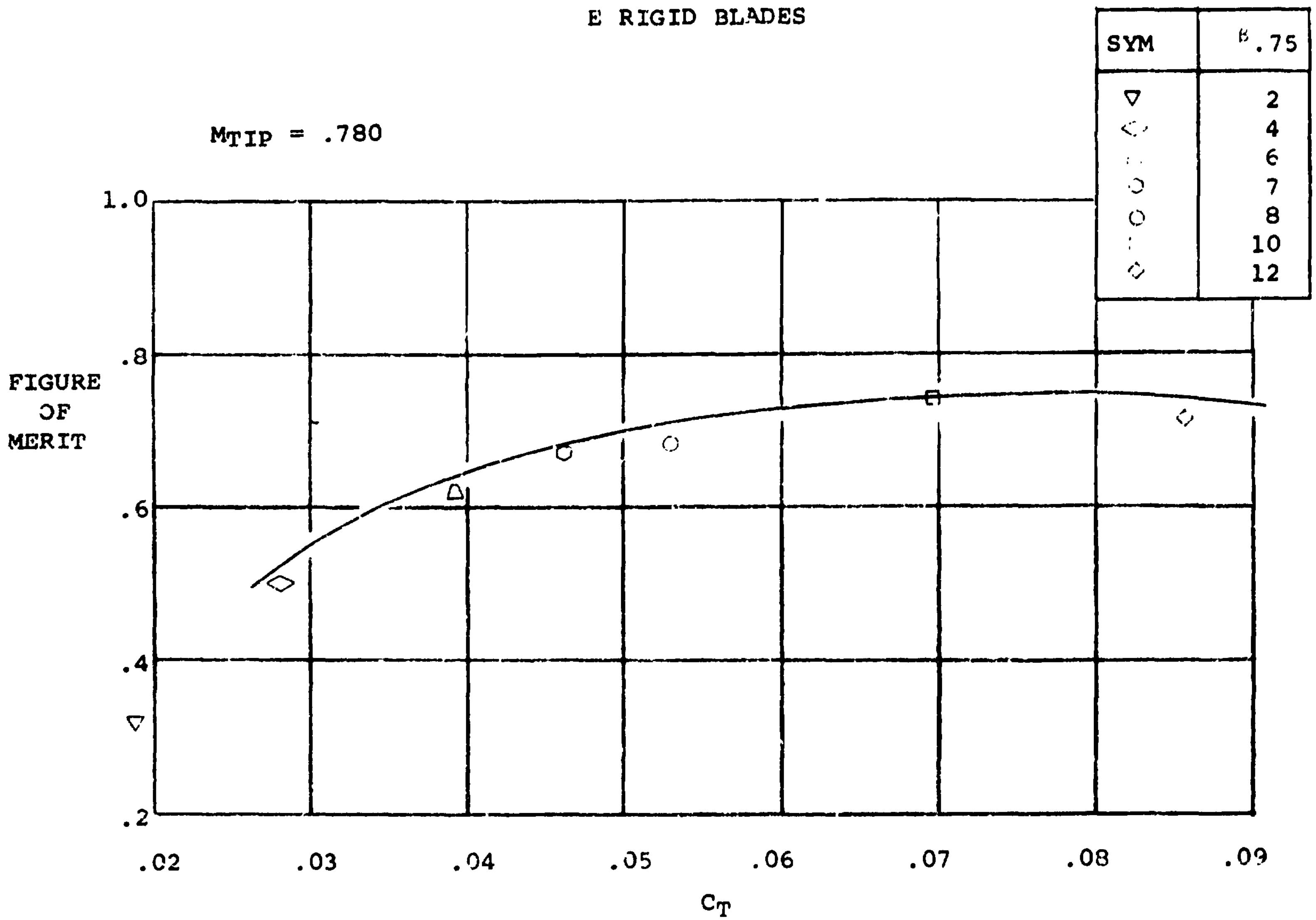


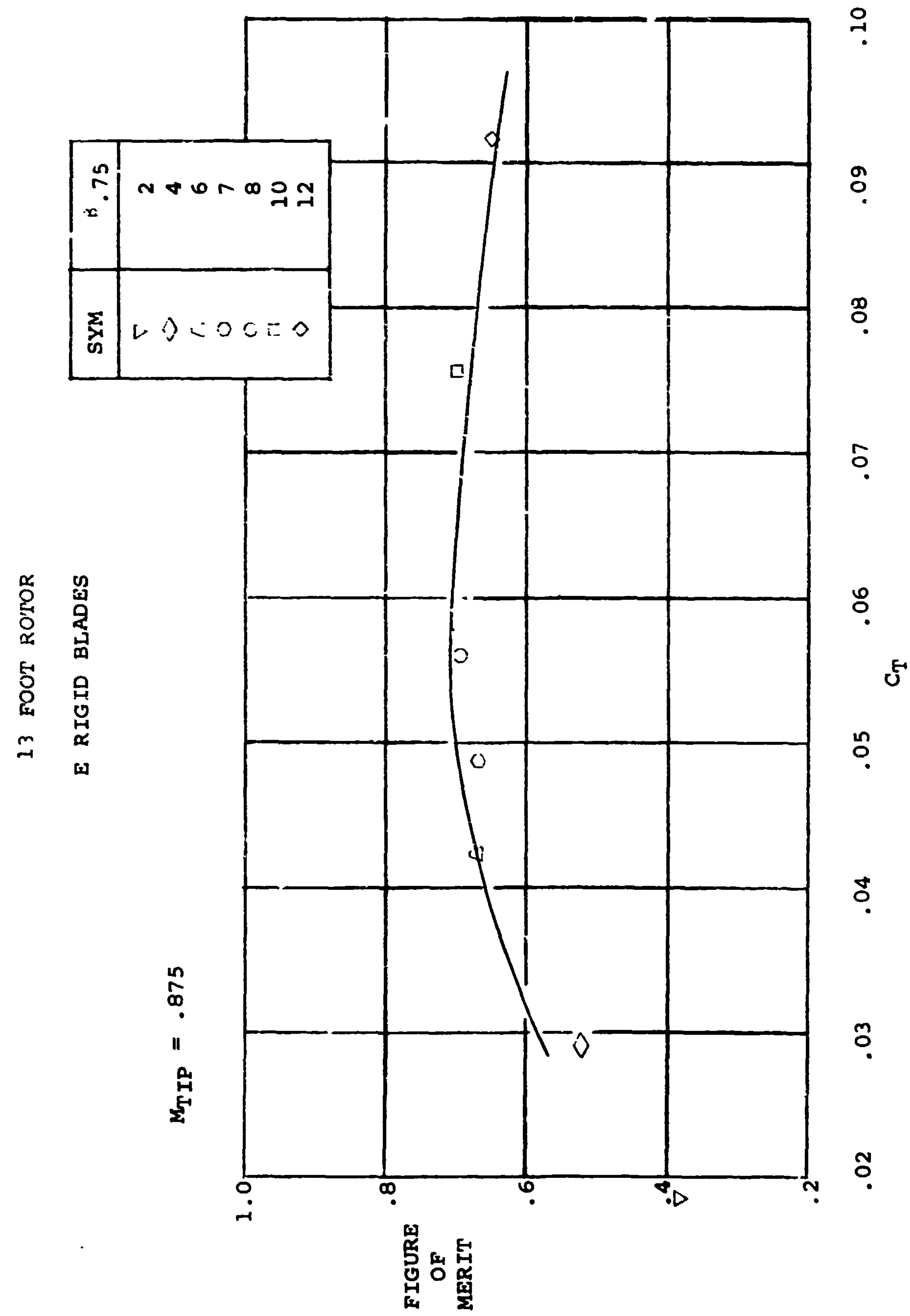

13 FOOT ROTOR
E RIGID BLADES
M_TIP = .596
SYM
β .75
2
4
6
7
8
10
12
14
16
OPEN SYMBOLS - ALUMINUM BLADES
SOLID SYMBOLS - DYNAMICALLY SCALED
FIGURE OF MERIT
1.0
.8
.6
.4
.2
C_T
.02
.03
.04
.05
.06
.07
.08
.09
.10

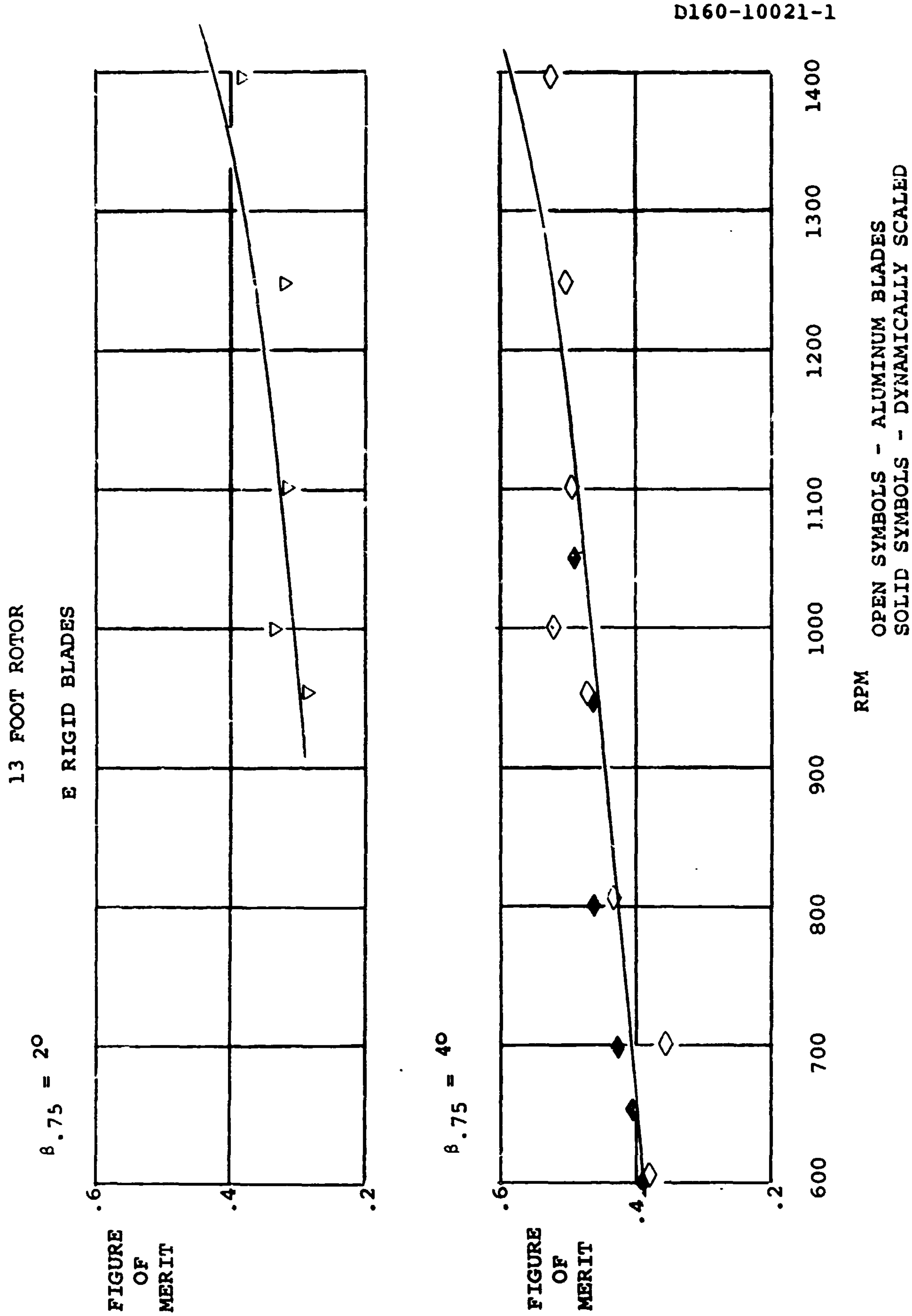

13 FOOT ROTOR
E RIGID BLADES
M_{TIP} = .689
SYM
$\beta_{.75}$
2
4
6
7
8
10
11
12
13
14
FIGURE OF MERIT
1.0
.8
.6
.4
.2
.02
.03
.04
.05
.06
.07
.08
.09
.10
C_T
OPEN SYMBOLS - ALUMINUM BLADES
SOLID SYMBOLS - DYNAMICALLY SCALED

13 FOOT ROTOR

E RIGID BLADES

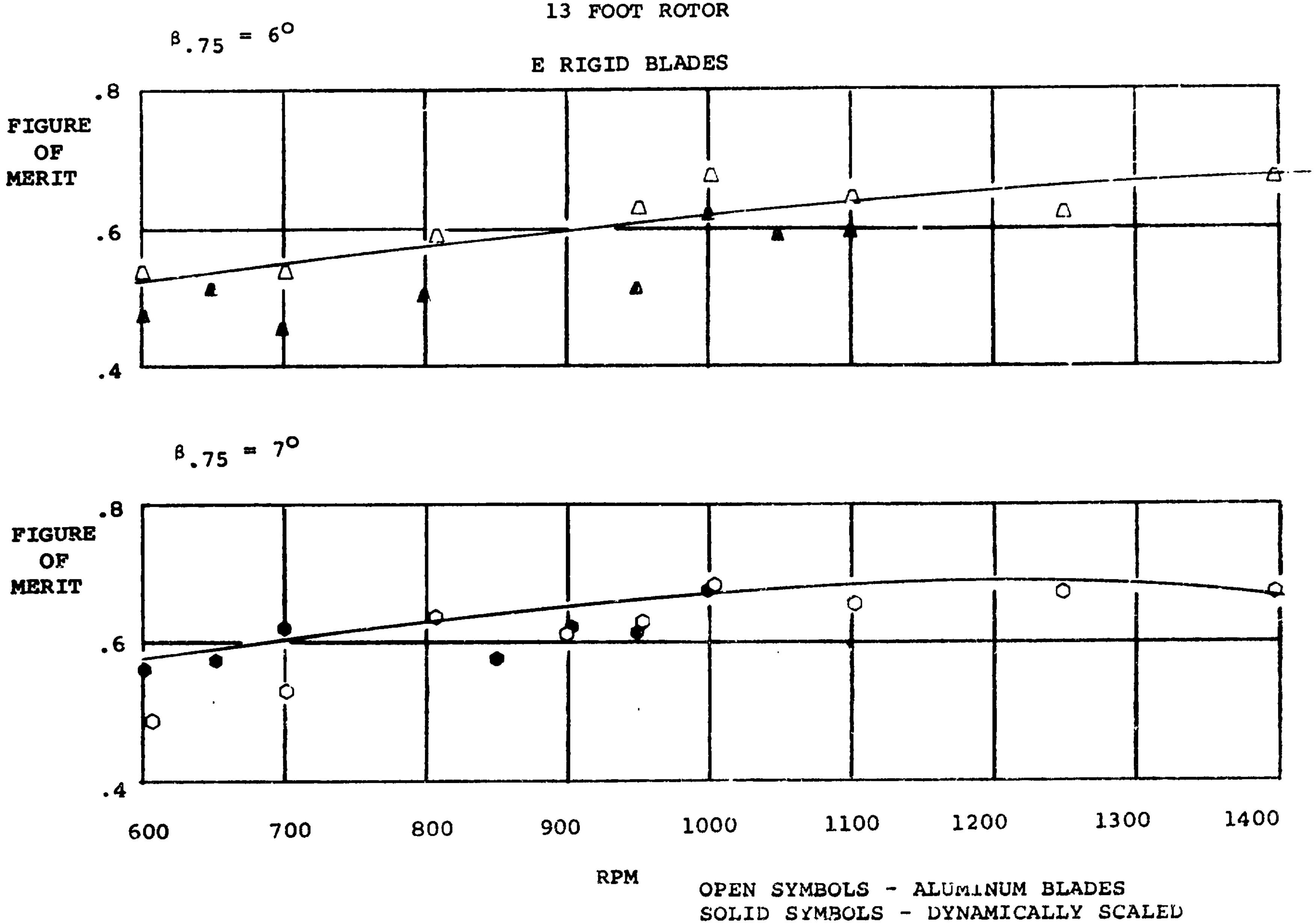



13 FOOT ROTOR
E RIGID BLADES
M_{TIP} = .875
SYM
θ .75
2
4
6
7
8
10
12
FIGURE OF MERIT
1.0
.8
.6
.4
.2
.02
.03
.04
.05
.06
.07
.08
.09
.10
C_T


13 FOOT ROTOR
E RIGID BLADES
β.75 = 2°
β.75 = 4°
FIGURE OF MERIT
FIGURE OF MERIT
.6
.4
.2
.6
.4
.2
600
700
800
900
1000
1100
1200
1300
1400
RPM
OPEN SYMBOLS - ALUMINUM BLADES
SOLID SYMBOLS - DYNAMICALLY SCALED

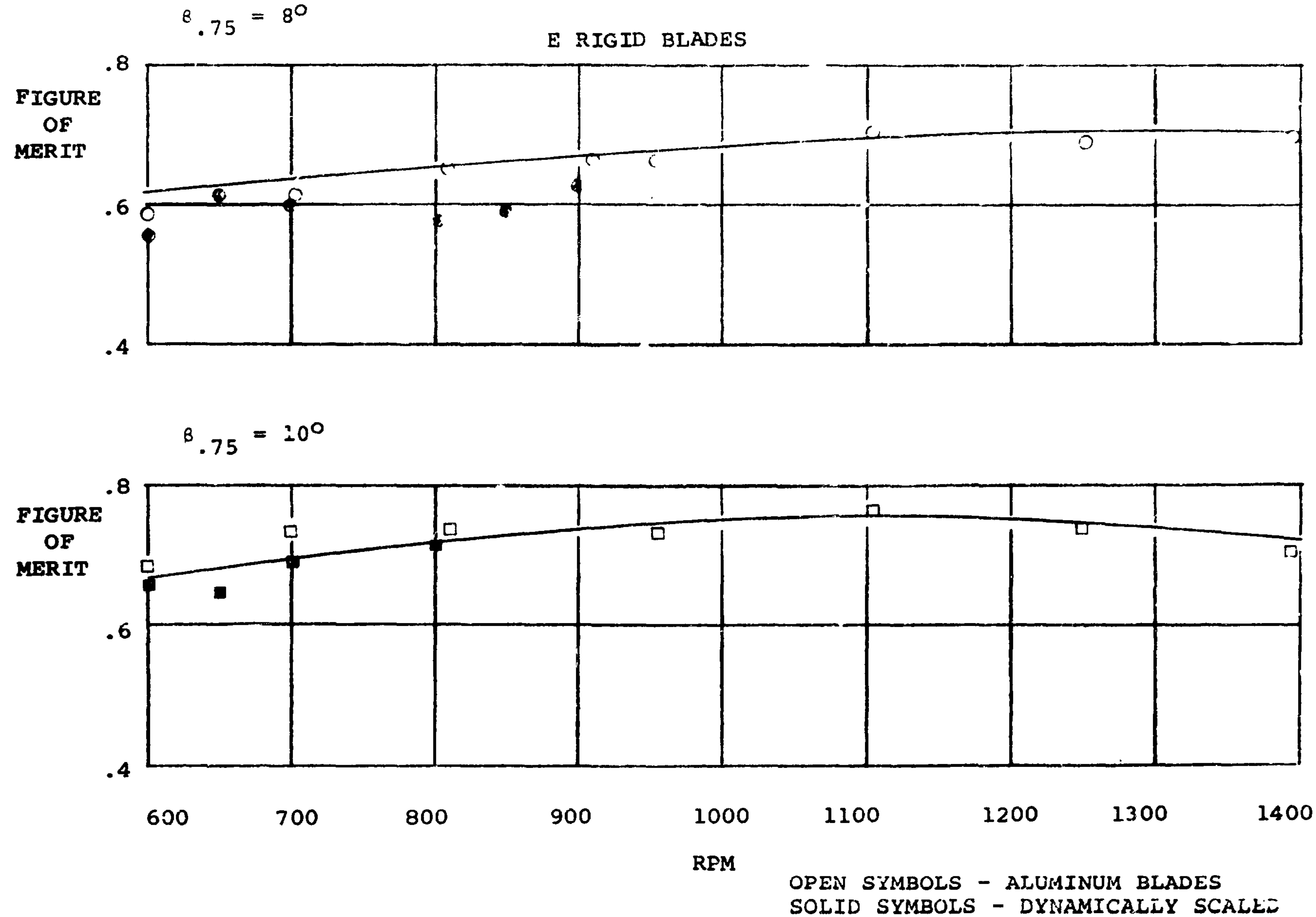
13 FOOT ROTOR

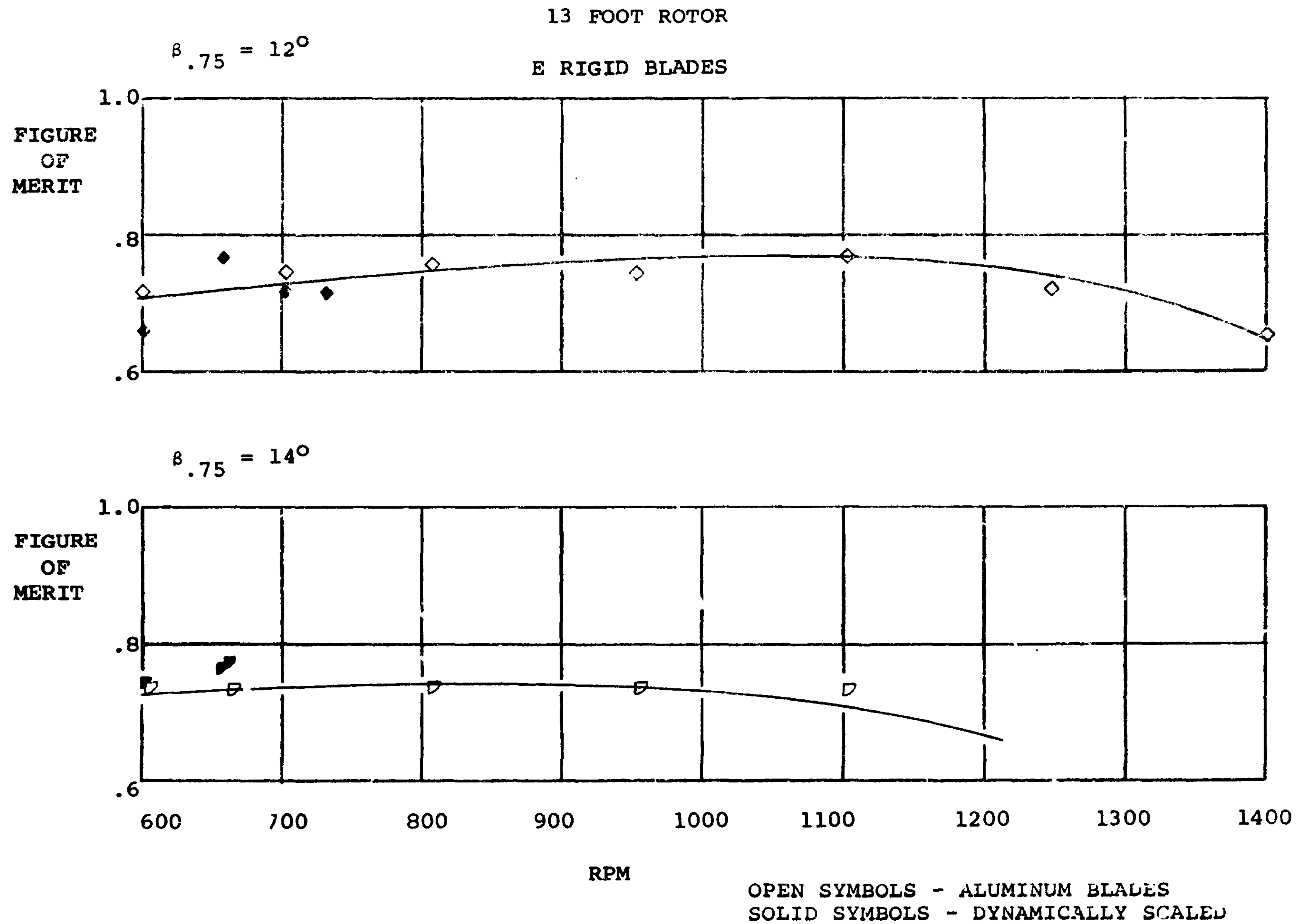
E RIGID BLADES



13 FOOT ROTOR

E RIGID BLADES

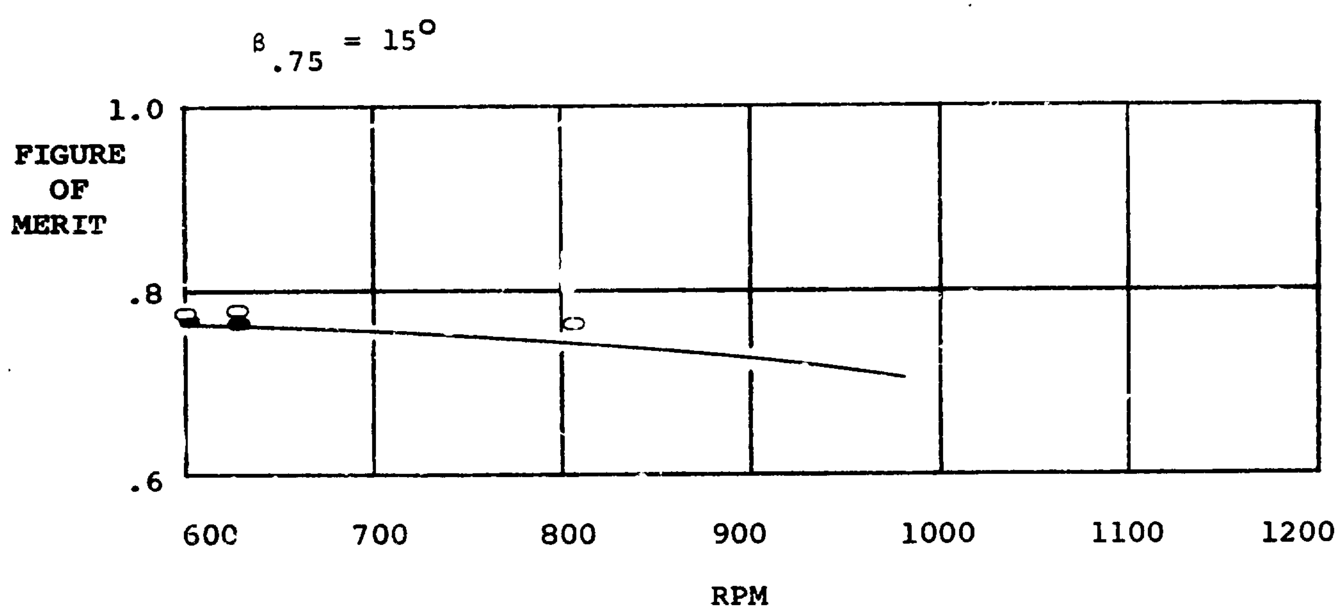



13 FOOT ROTOR
E RIGID BLADES
β.75 = 12°
β.75 = 14°
FIGURE OF MERIT
1.0
.8
.6
600
700
800
900
1000
1100
1200
1300
1400
RPM
OPEN SYMBOLS - ALUMINUM BLADES
SOLID SYMBOLS - DYNAMICALLY SCALED

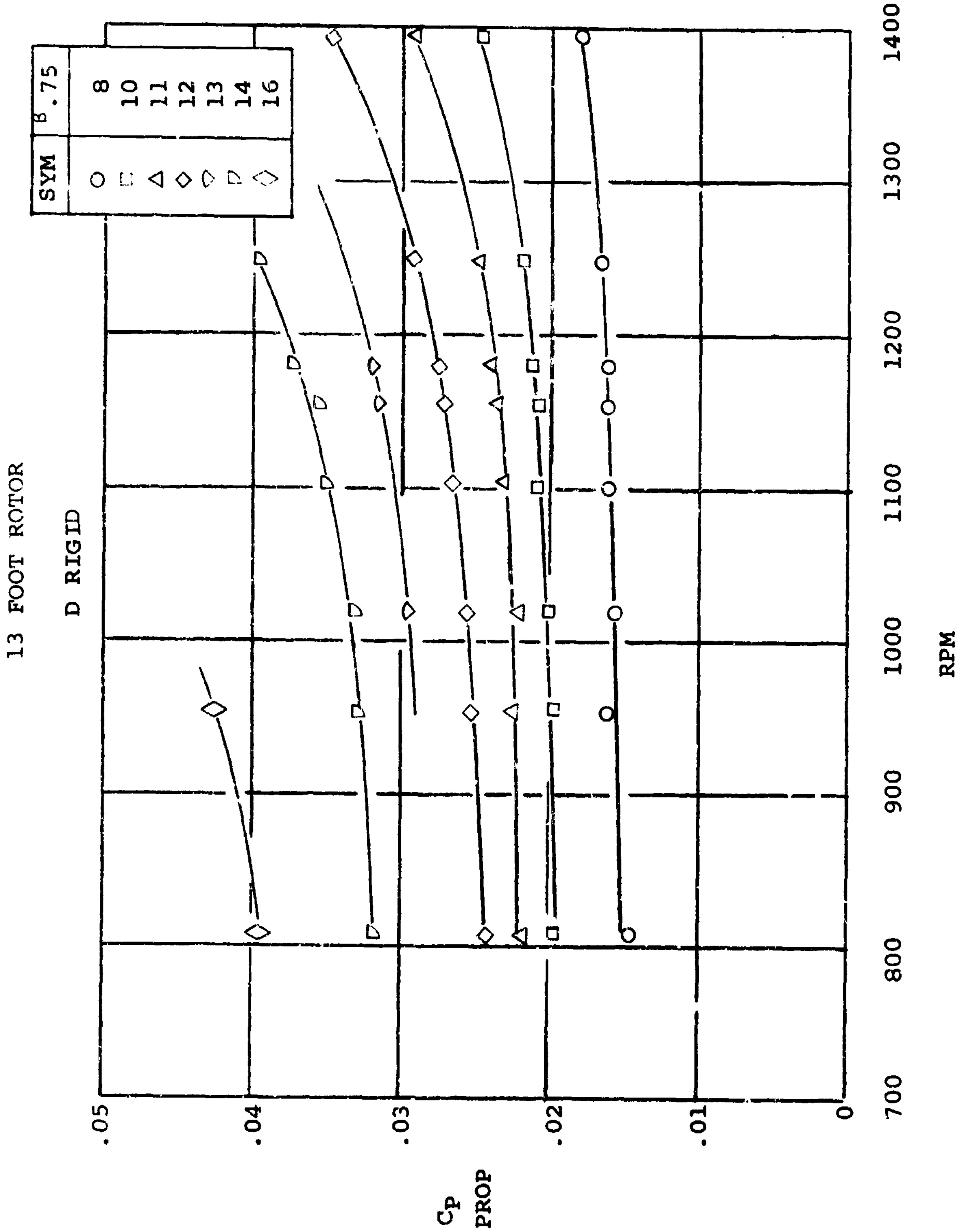
13 FOOT ROTOR

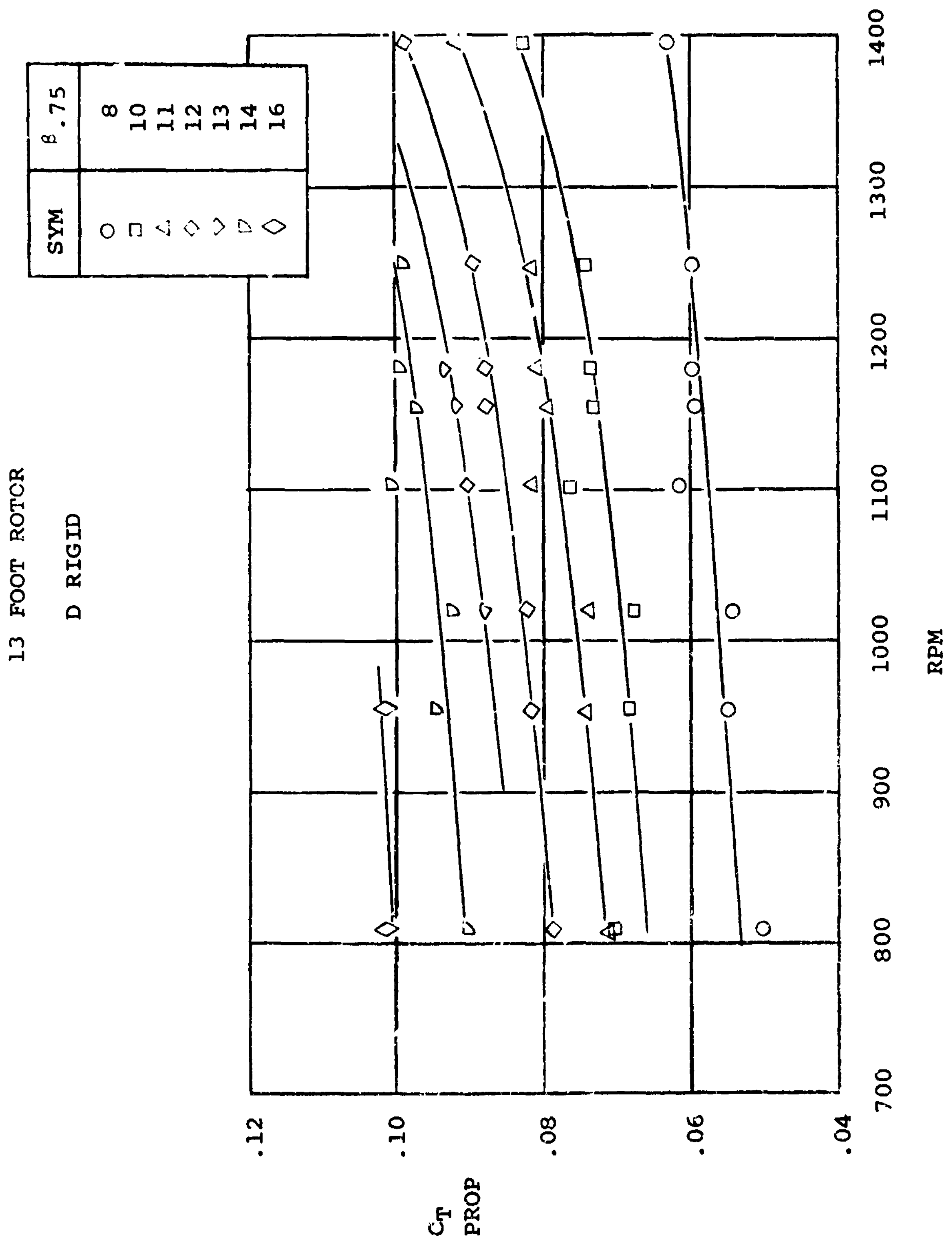
E RIGID BLADES

OPEN SYMBOLS - ALUMINUM BLADES
SOLID SYMBOLS - DYNAMICALLY SCALED



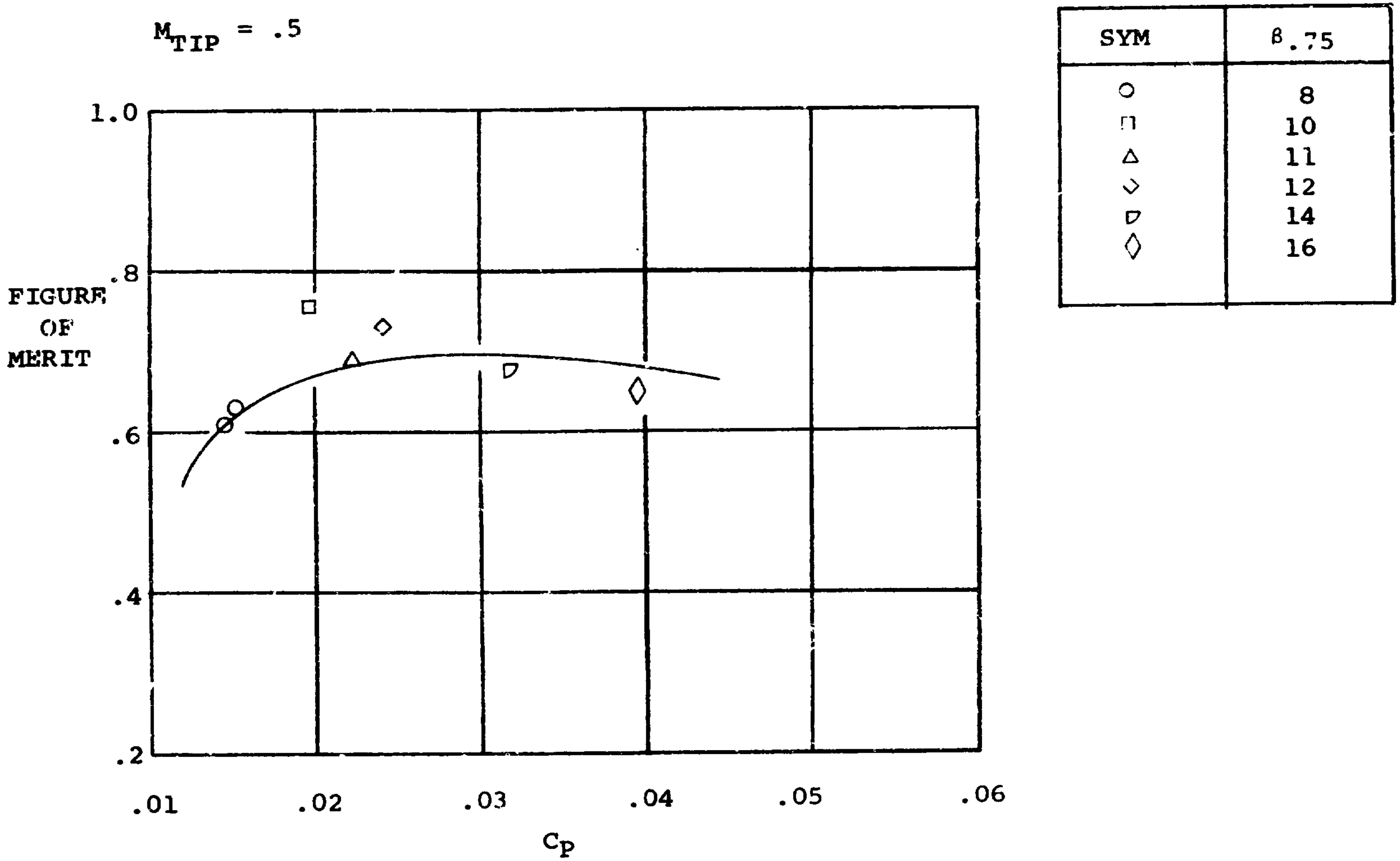
6.2 D BLADE STATIC DATA


13 FOOT ROTOR
D RIGID
SYM
β .75
8
10
11
12
13
14
16
C_P PROP
.05
.04
.03
.02
.01
0
RPM
700
800
900
1000
1100
1200
1300
1400


13 FOOT ROTCR
D RIGID
SYM
β .75
8
10
11
12
13
14
16
.12
.10
.08
.06
.04
C_T PROP
700
800
900
1000
1100
1200
1300
1400
RPM

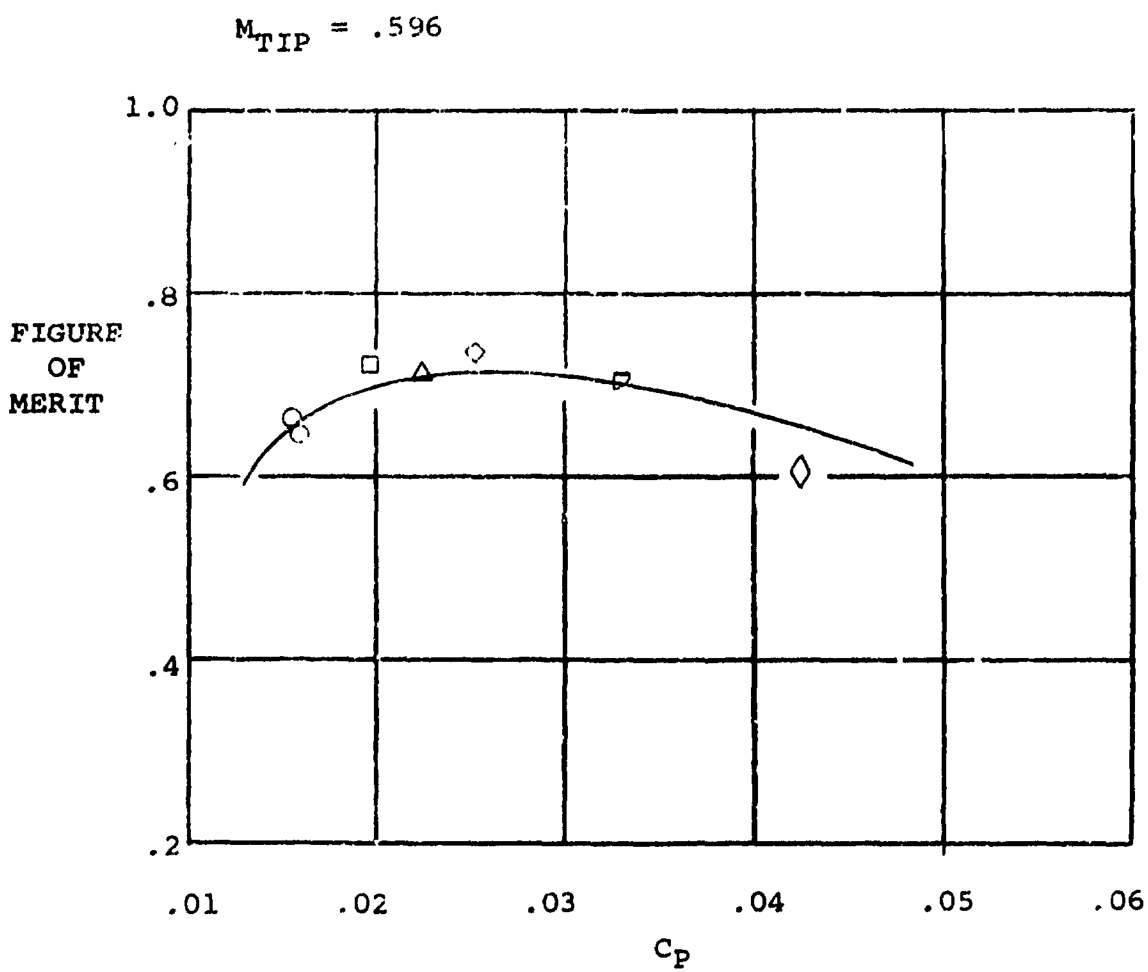
13 FOOT ROTOR

D RIGID BLADES



13 FOOT ROTOR

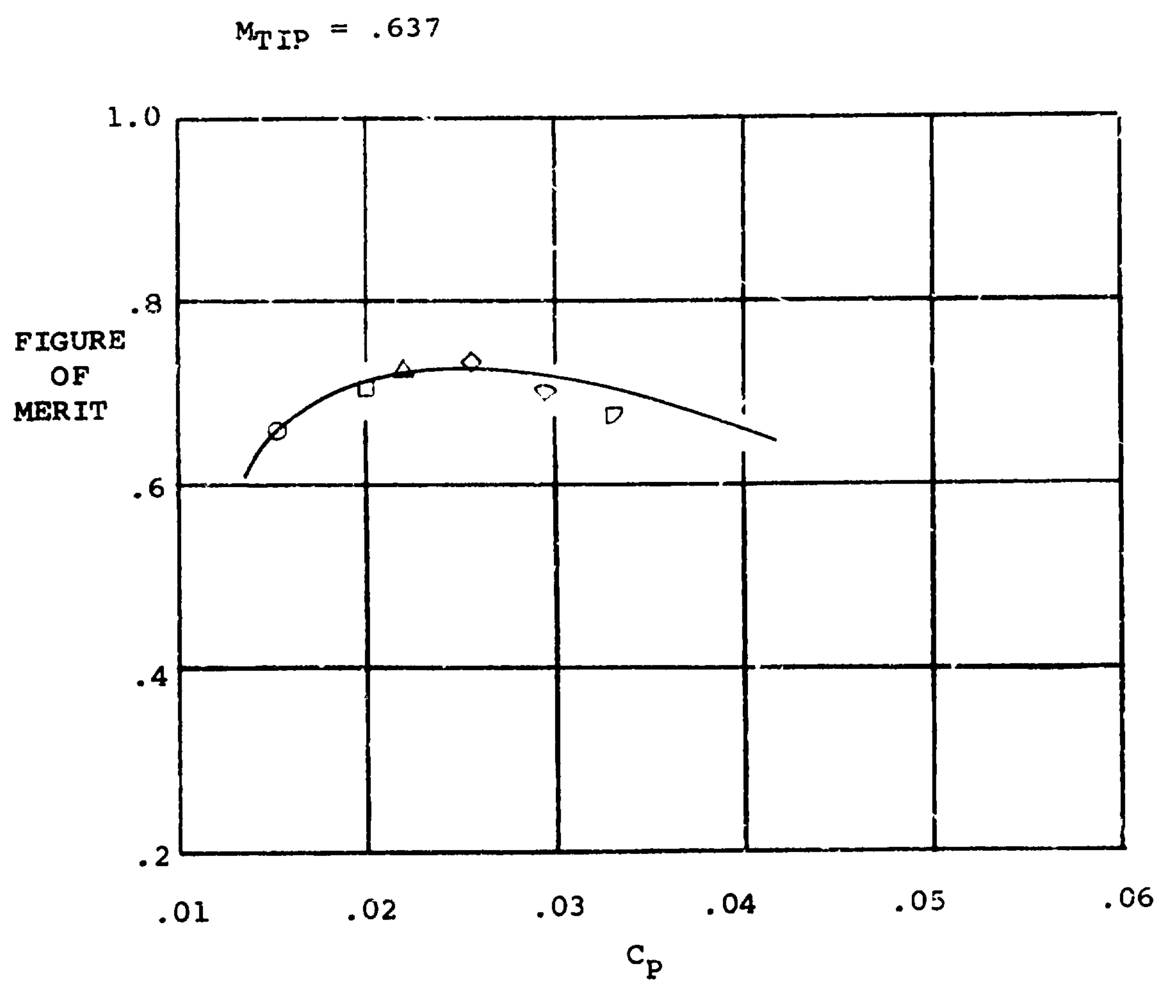
D RIGID



SYM	$\beta_{.75}$
⊙	8
□	10
△	11
◇	12
▽	14
◇	16

13 FOOT ROTOR

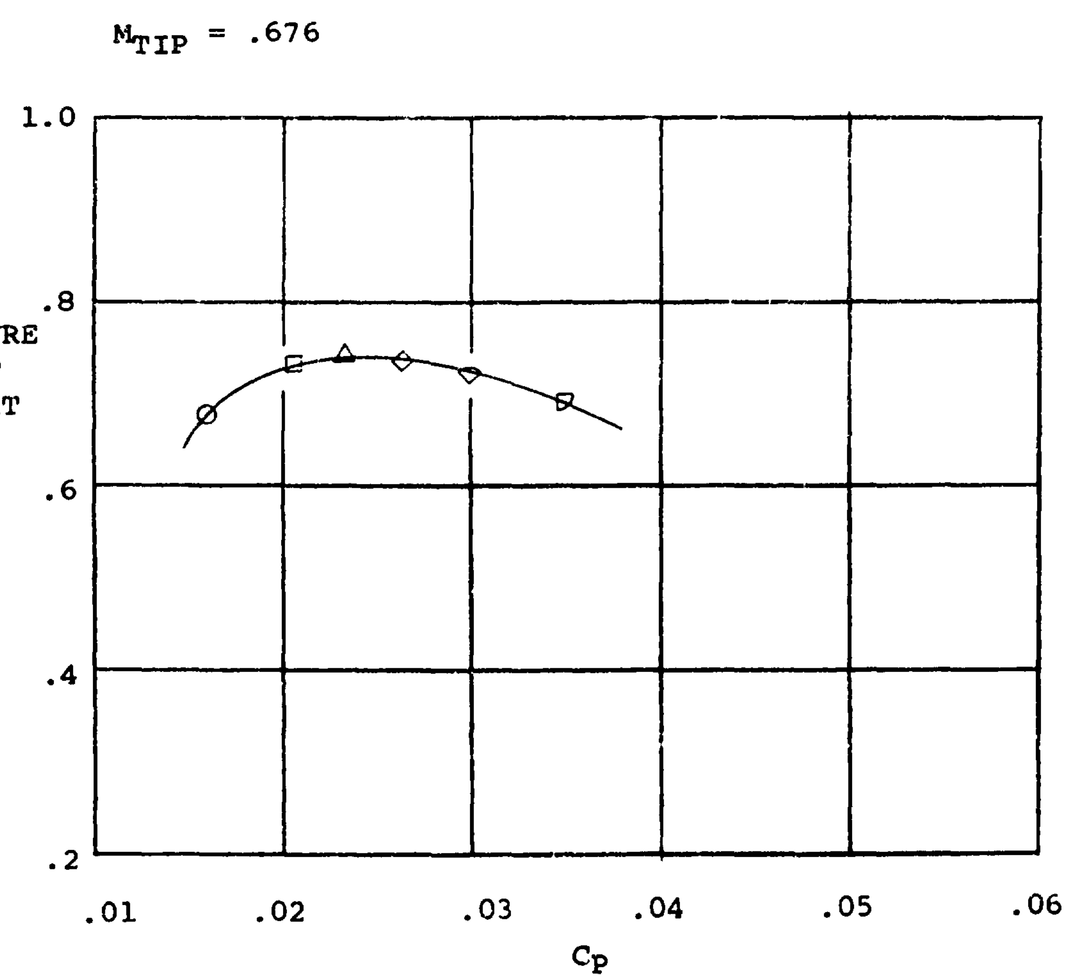
D RIGID BLADES



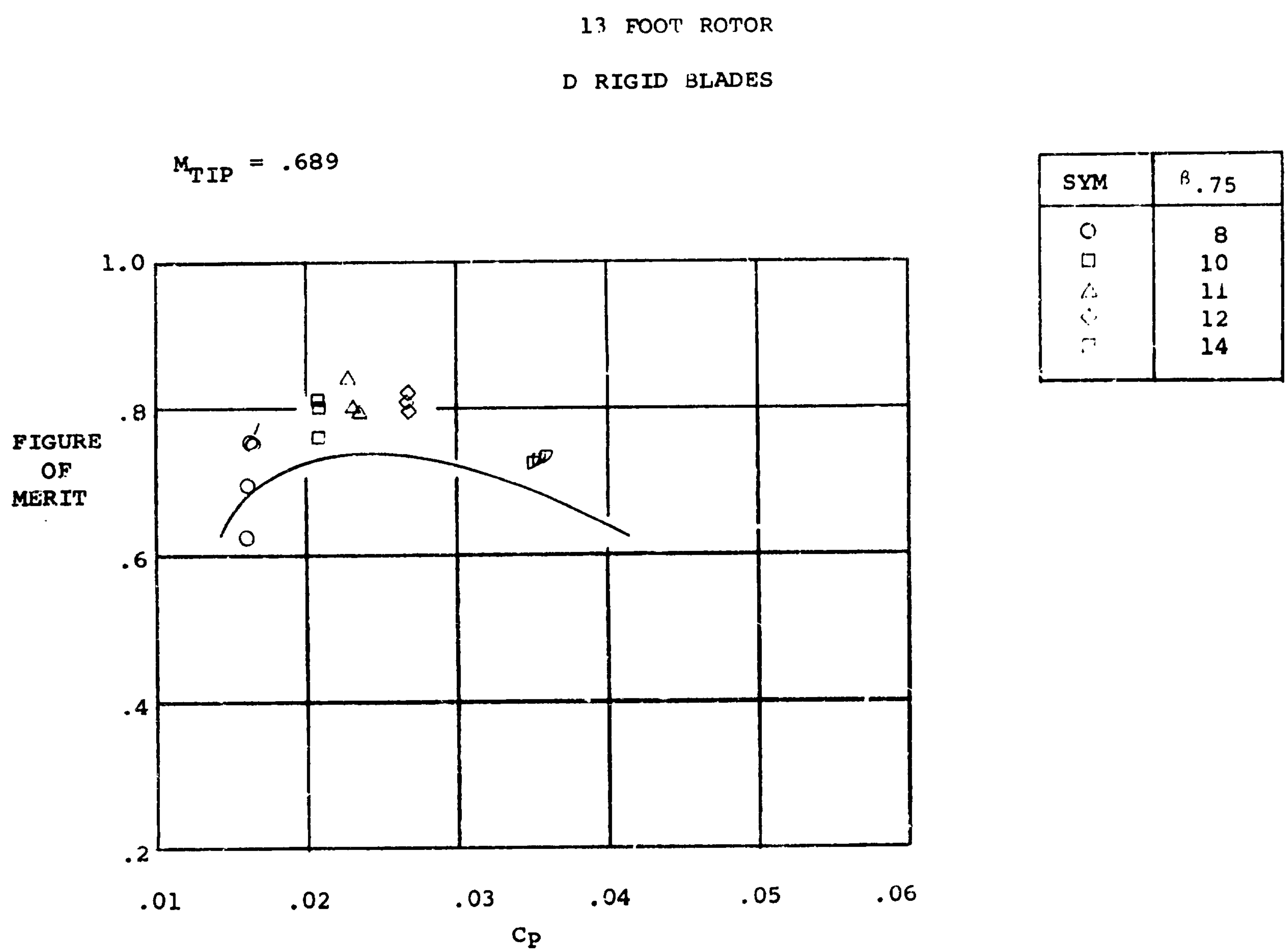
SYM	$\beta_{.75}$
○	8
□	10
△	11
◇	12
⬠	13
▷	14

13 FOOT ROTOR

D RIGID BLADES

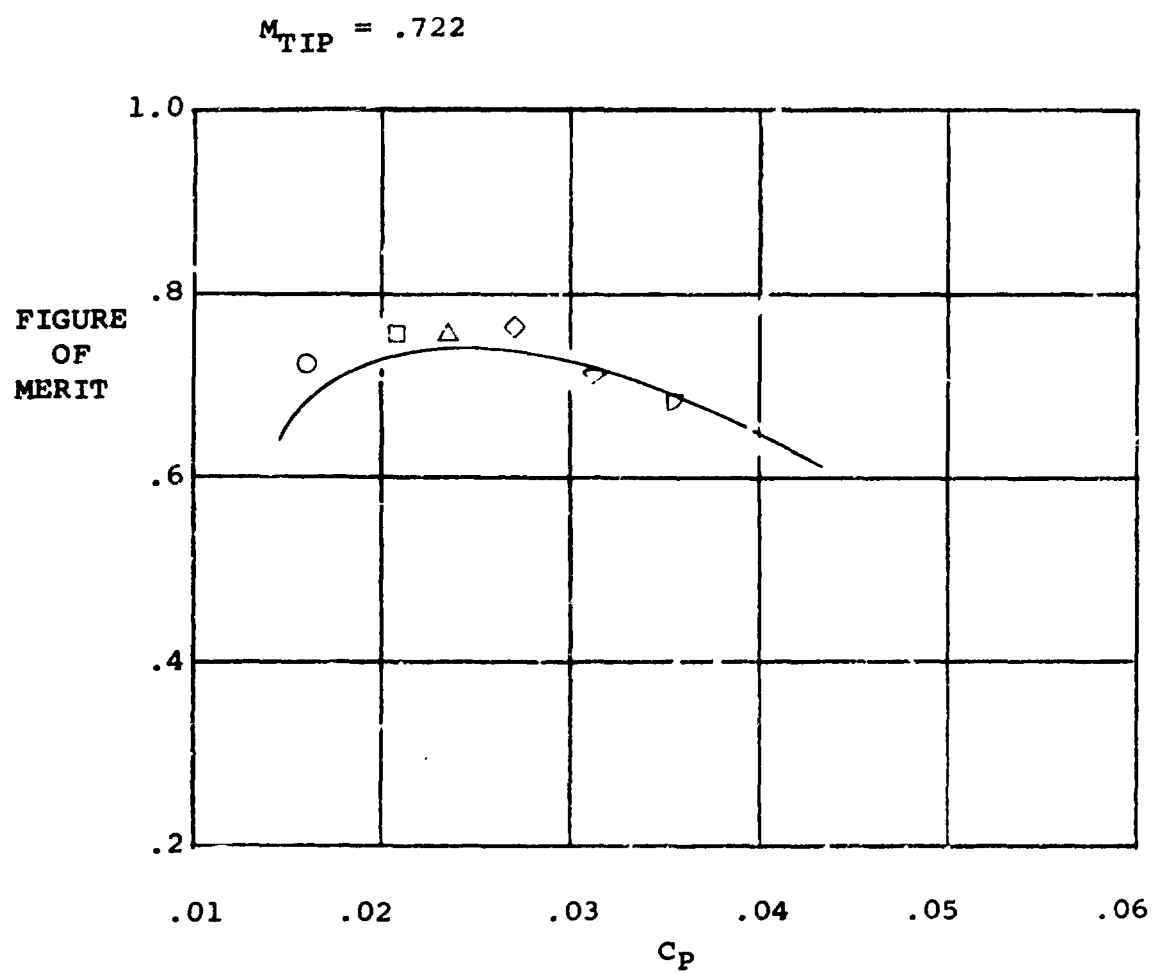


SYM	$\beta_{.75}$
○	8
□	10
△	11
◇	12
▽	13
⌐	14


13 FOOT ROTOR
D RIGID BLADES
M_{TIP} = .689
SYM
$\beta_{.75}$
8
10
11
12
14
FIGURE OF MERIT
1.0
.8
.6
.4
.2
.01
.02
.03
.04
.05
.06
C_P

13 FOOT ROTOR

D RIGID BLADES



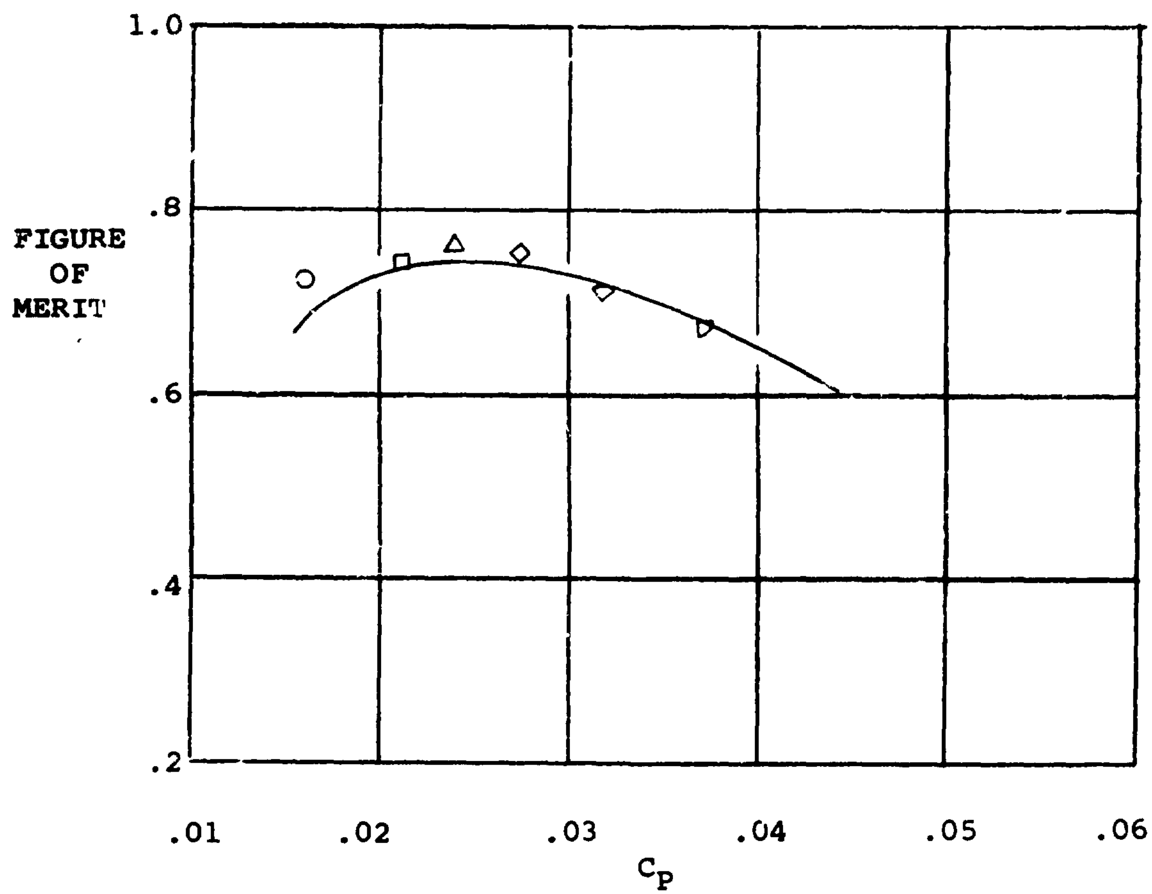
SYM	$\beta_{.75}$
○	8
□	10
△	11
◇	12
◁	13
◁	14

13 FOOT ROTOR

D RIGID BLADES

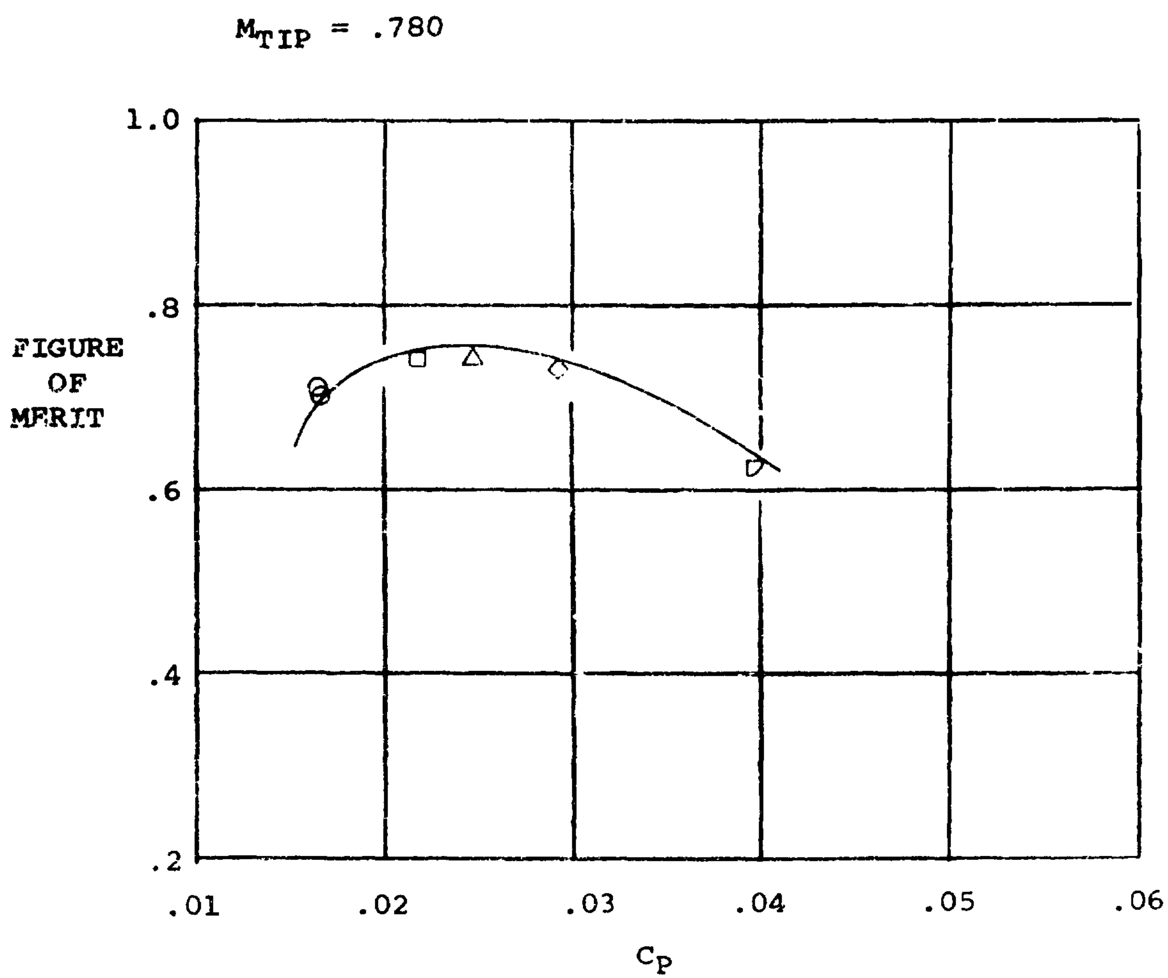
$M_{TIP} = .737$

SYM	$\beta_{.75}$
○	8
□	10
△	11
◇	12
◇	13
▽	14

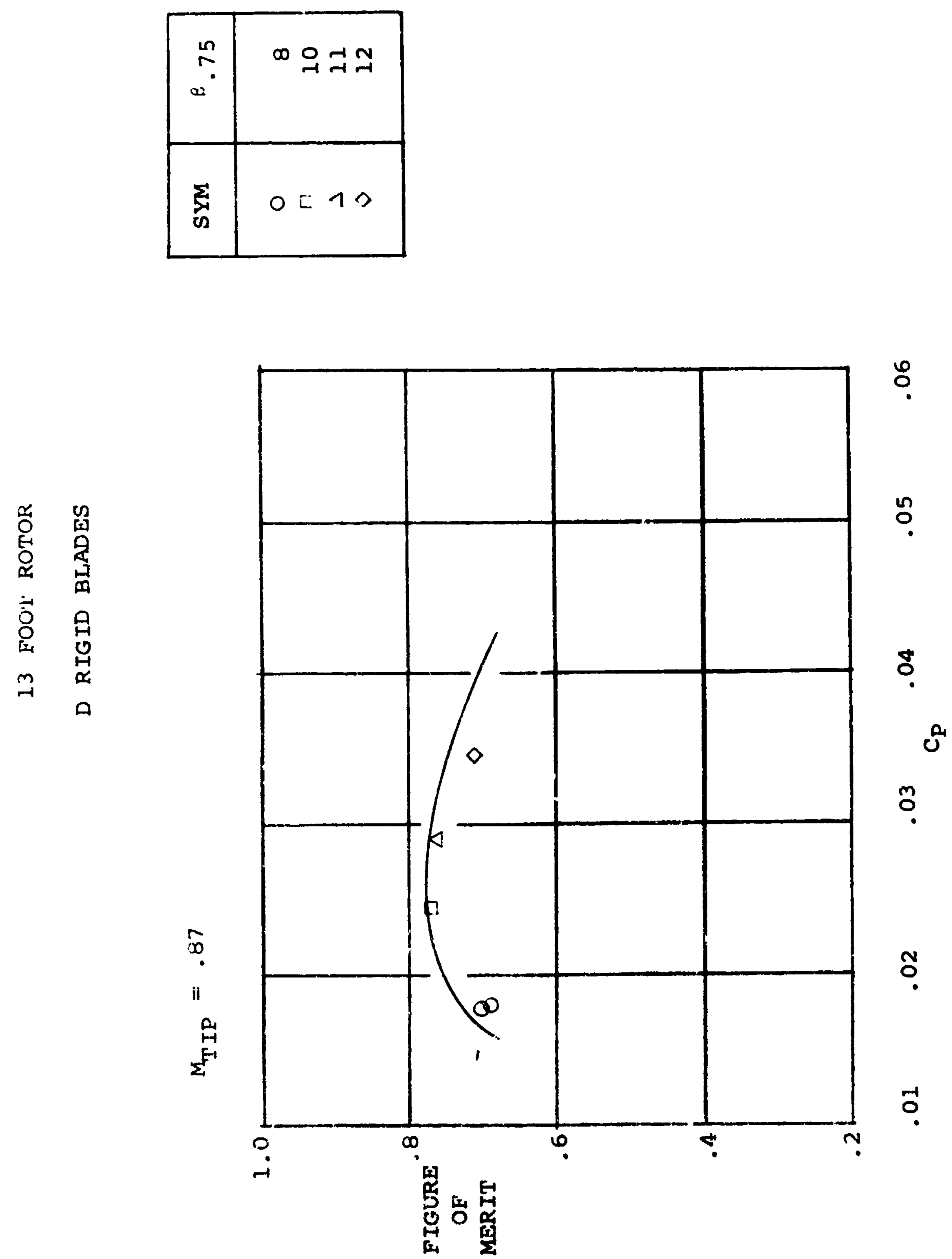


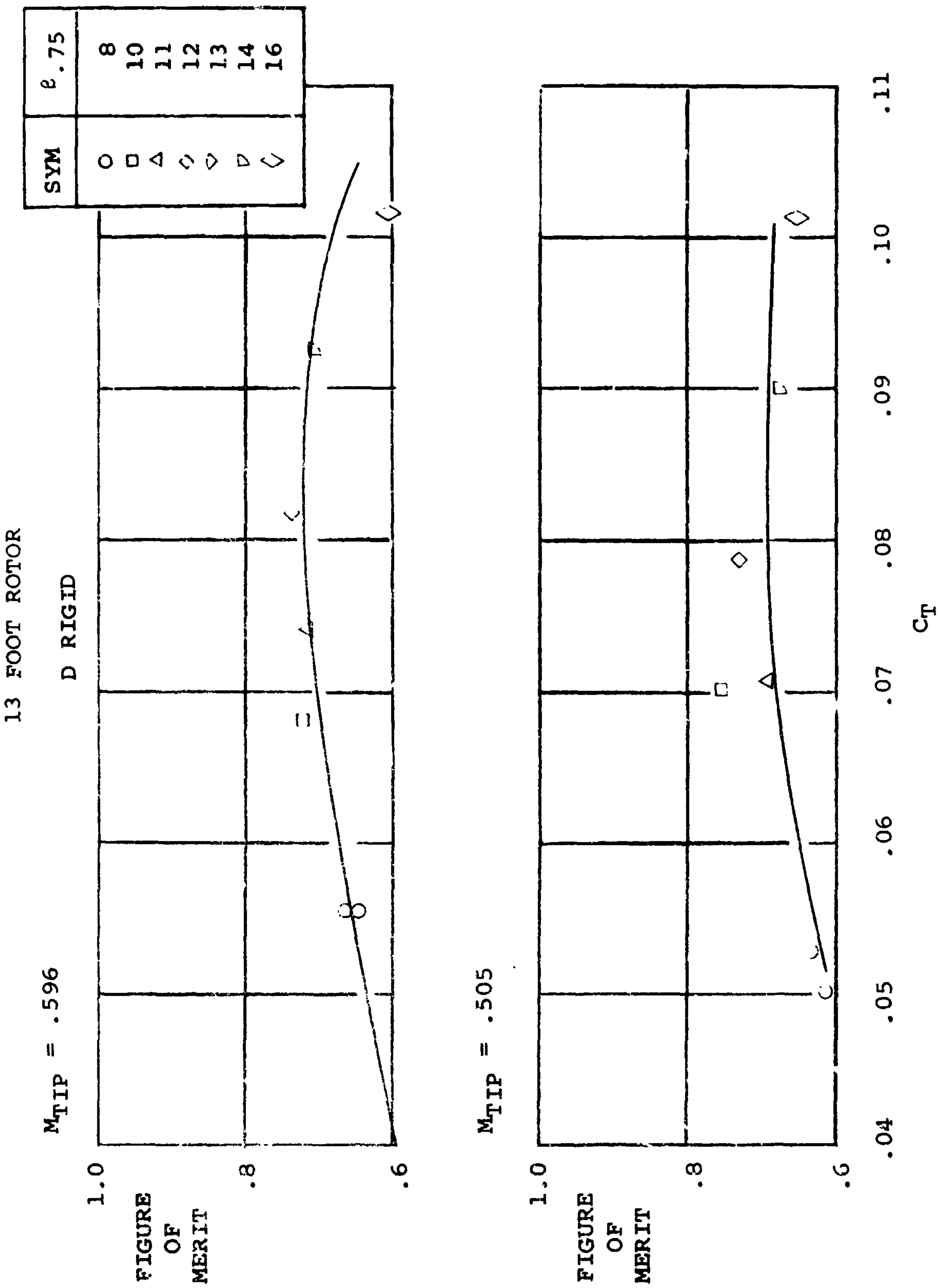
13 FOOT ROTOR

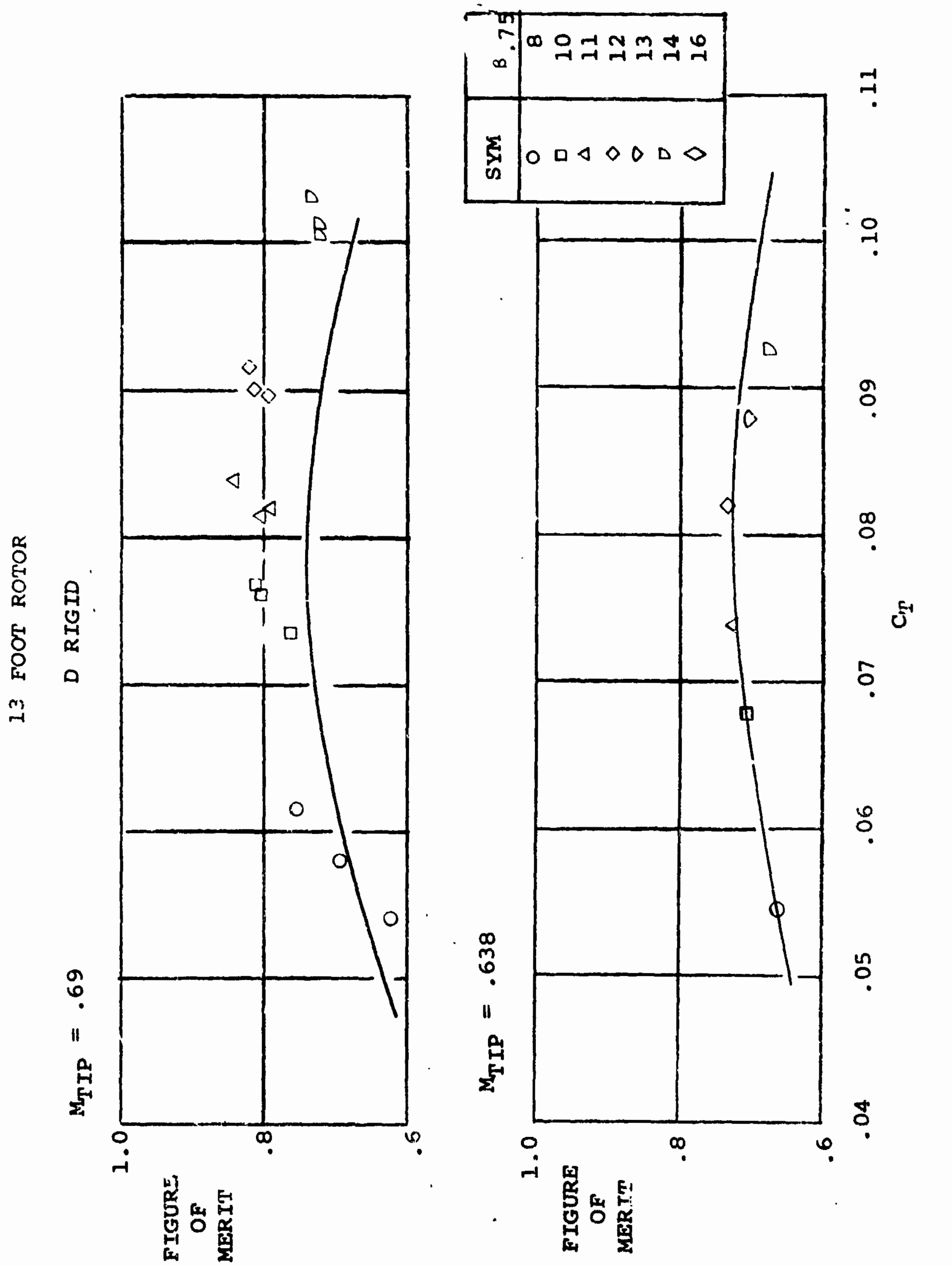
D RIGID BLADES

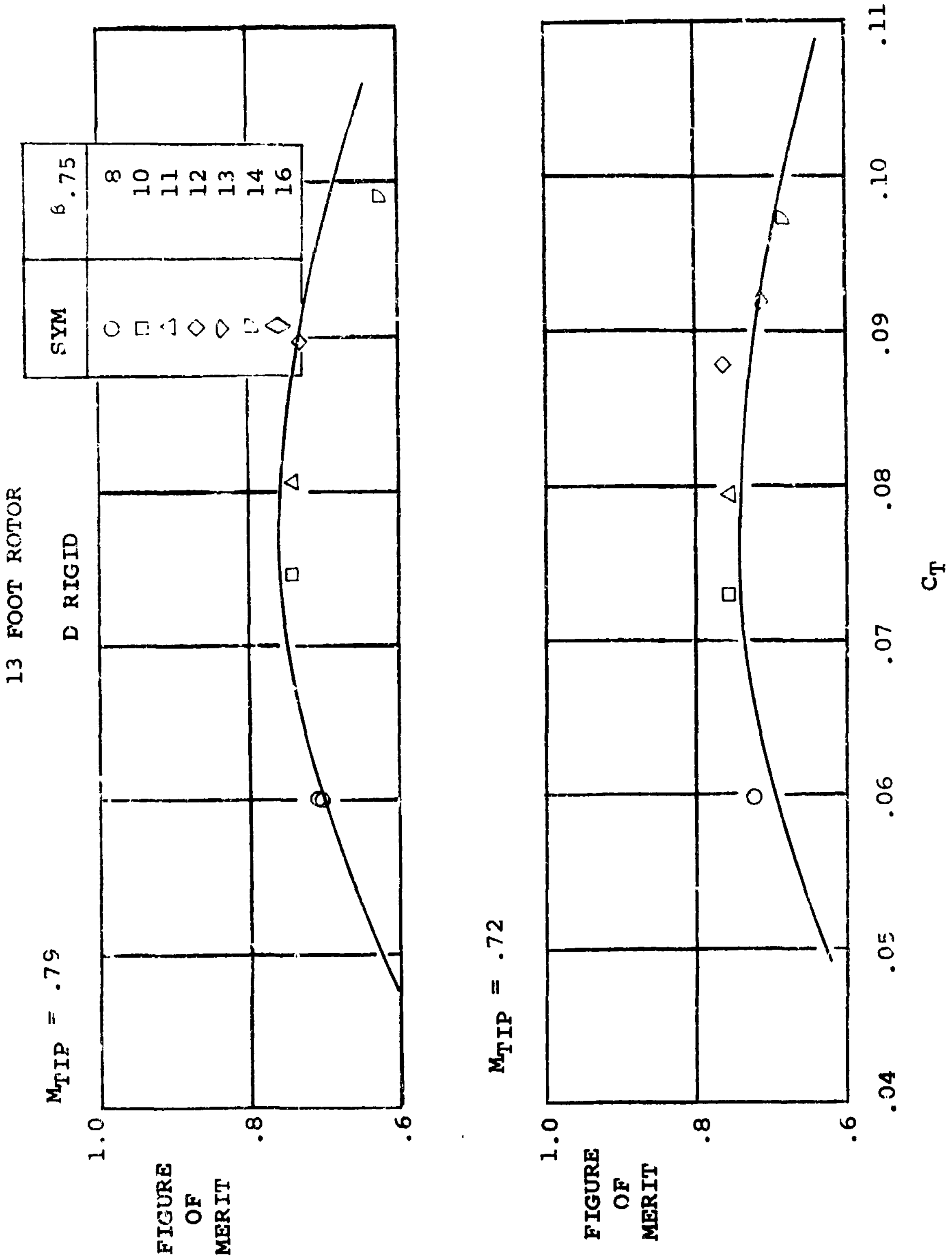


SYM	$\theta_{.75}$
○	8
□	10
△	11
◇	12
◸	14


13 FOOT ROTOR
D RIGID BLADES
M_{TIP} = .87
SYM
$\beta_{.75}$
8
10
11
12
FIGURE OF MERIT
1.0
.8
.6
.4
.2
C_P
.01
.02
.03
.04
.05
.06


13 FOOT ROTOR
D RIGID
SYM
$\beta_{.75}$
8
10
11
12
13
14
16
M_{TIP} = .596
M_{TIP} = .505
1.0
.8
.6
FIGURE
OF
MERIT
.04
.05
.06
.07
.08
.09
.10
.11
C_T


13 FOOT ROTOR
D RIGID
M_TIP = .69
M_TIP = .638
FIGURE OF MERIT
1.0
.8
.6
C_T
.04
.05
.06
.07
.08
.09
.10
.11
SYM
θ.75
8
10
11
12
13
14
16



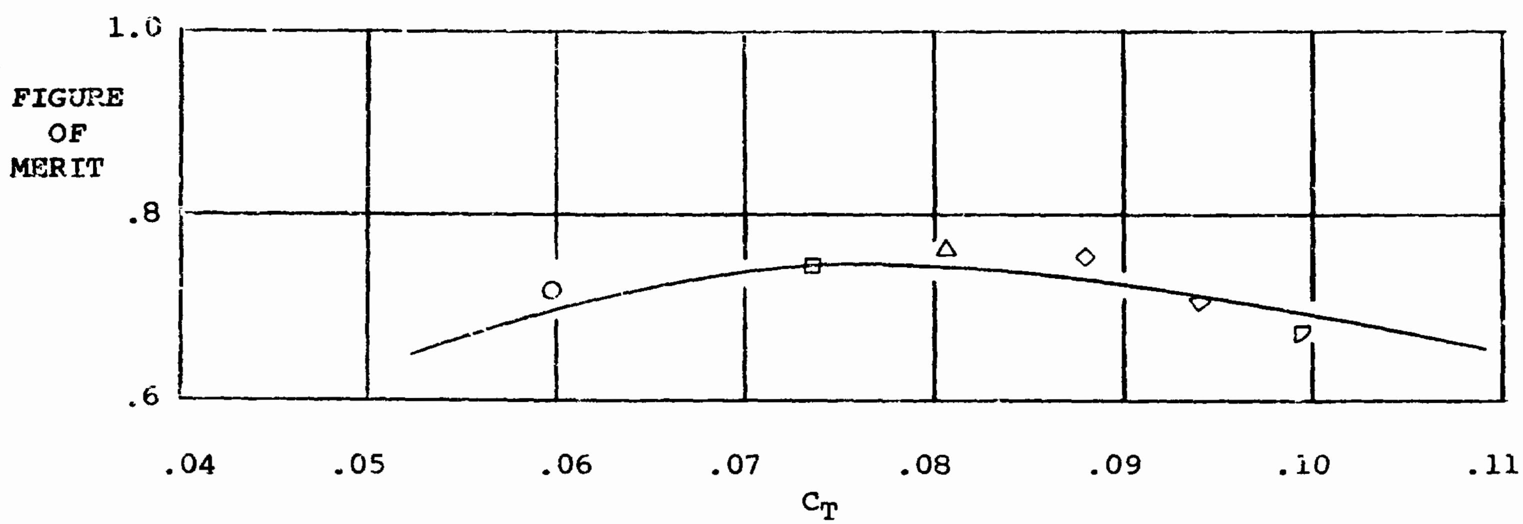
13 FOOT ROTOR
D RIGID
SYM
β.75
8
10
11
12
13
14
16
M_{TIP} = .79
M_{TIP} = .72
FIGURE OF MERIT
1.0
.8
.6
.04
.05
.06
.07
.08
.09
.10
.11
C_T

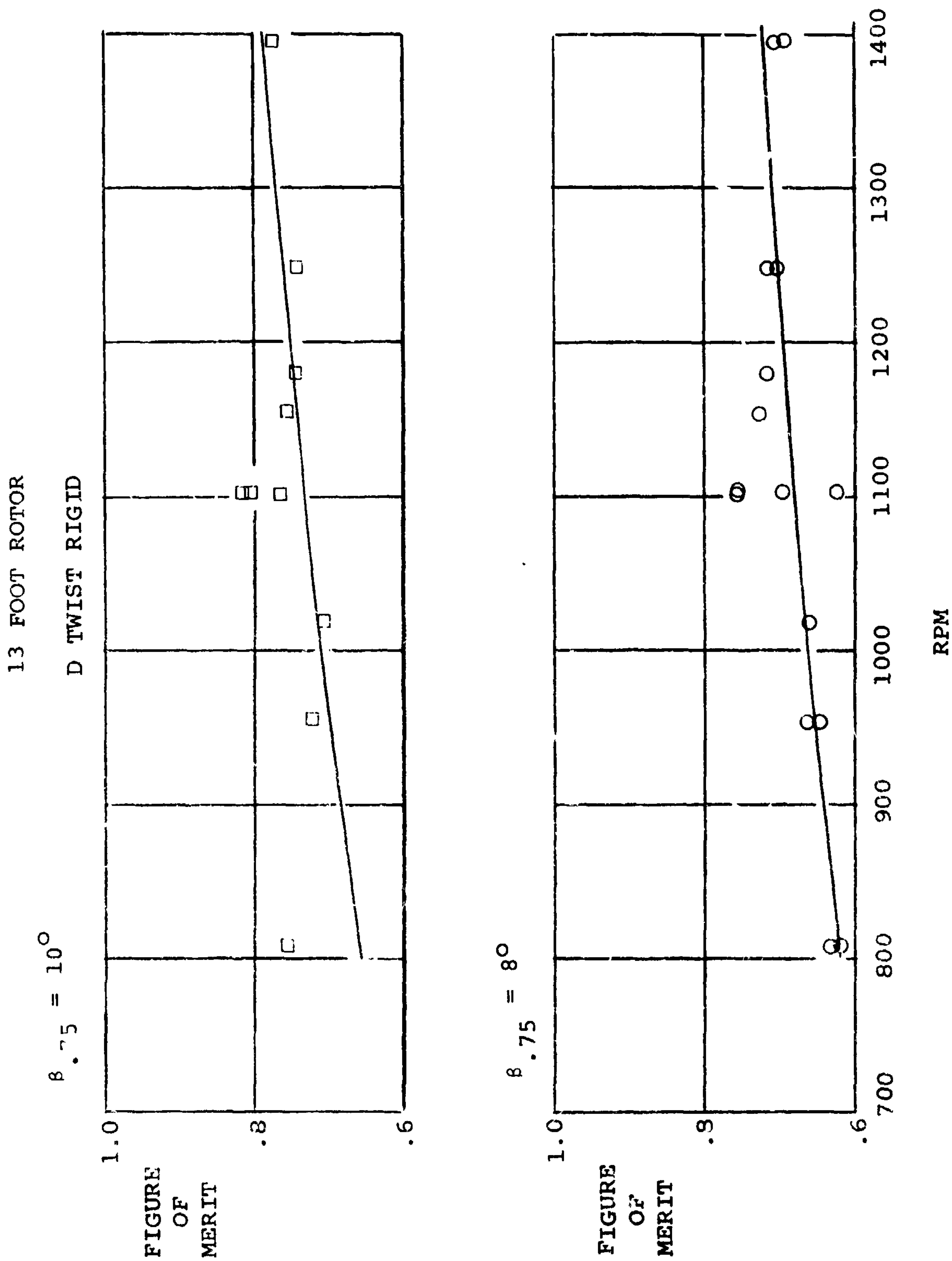
13 FOOT ROTOR

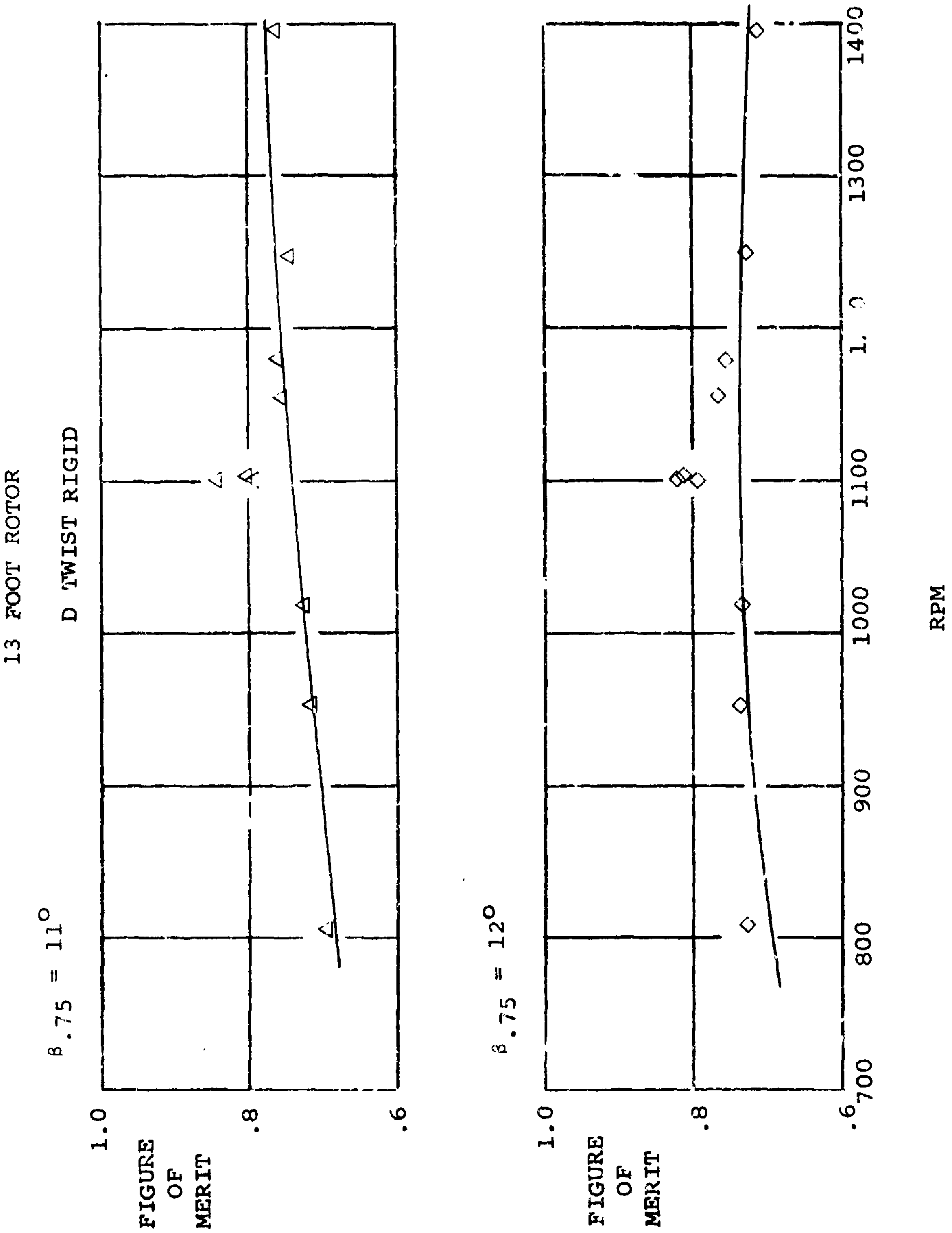
D RIGID

SYM	$\beta_{.75}$
○	8
□	10
△	11
◇	12
◁	13
◸	14
〈	16

$M_{TIP} = .74$

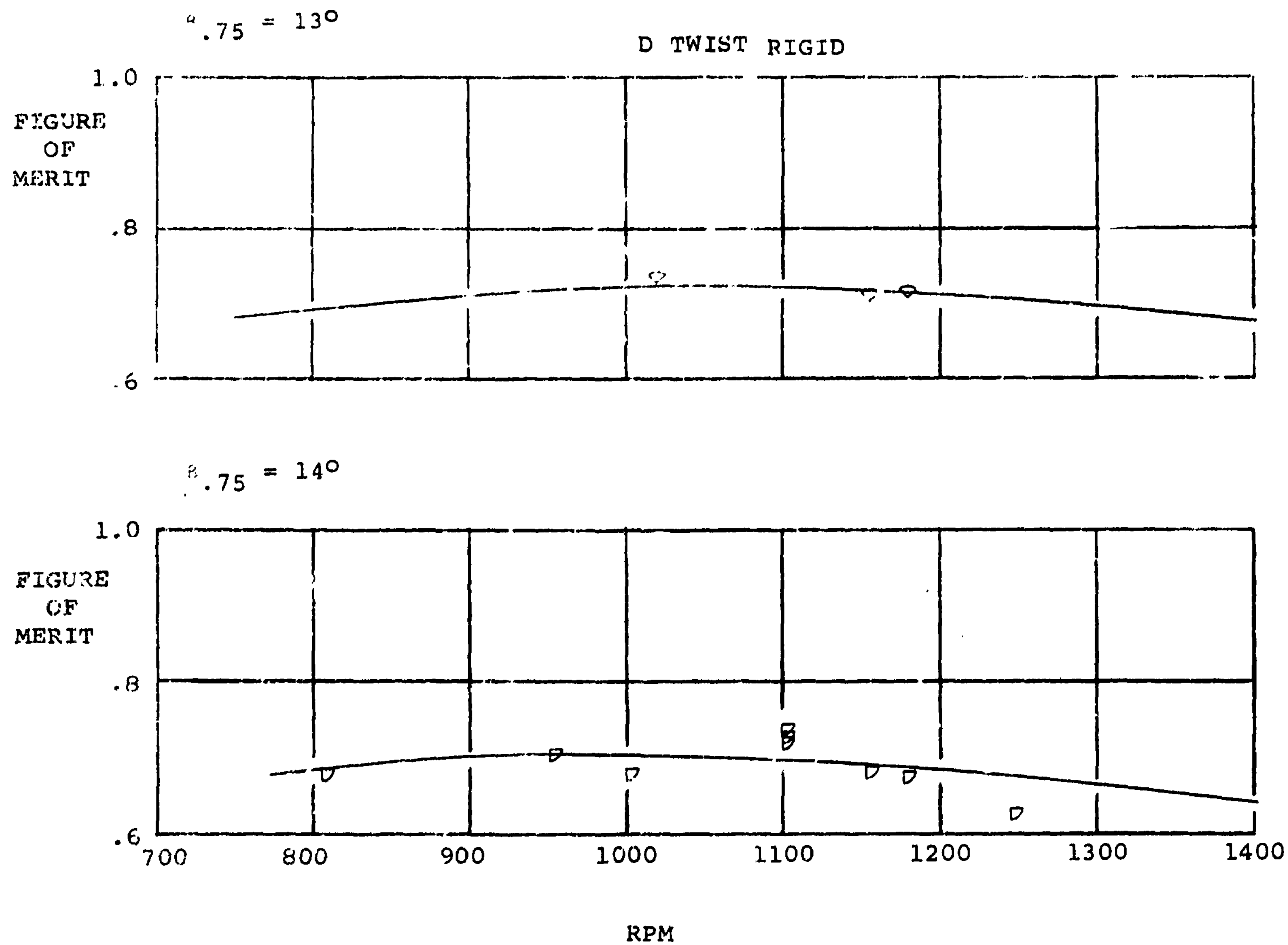


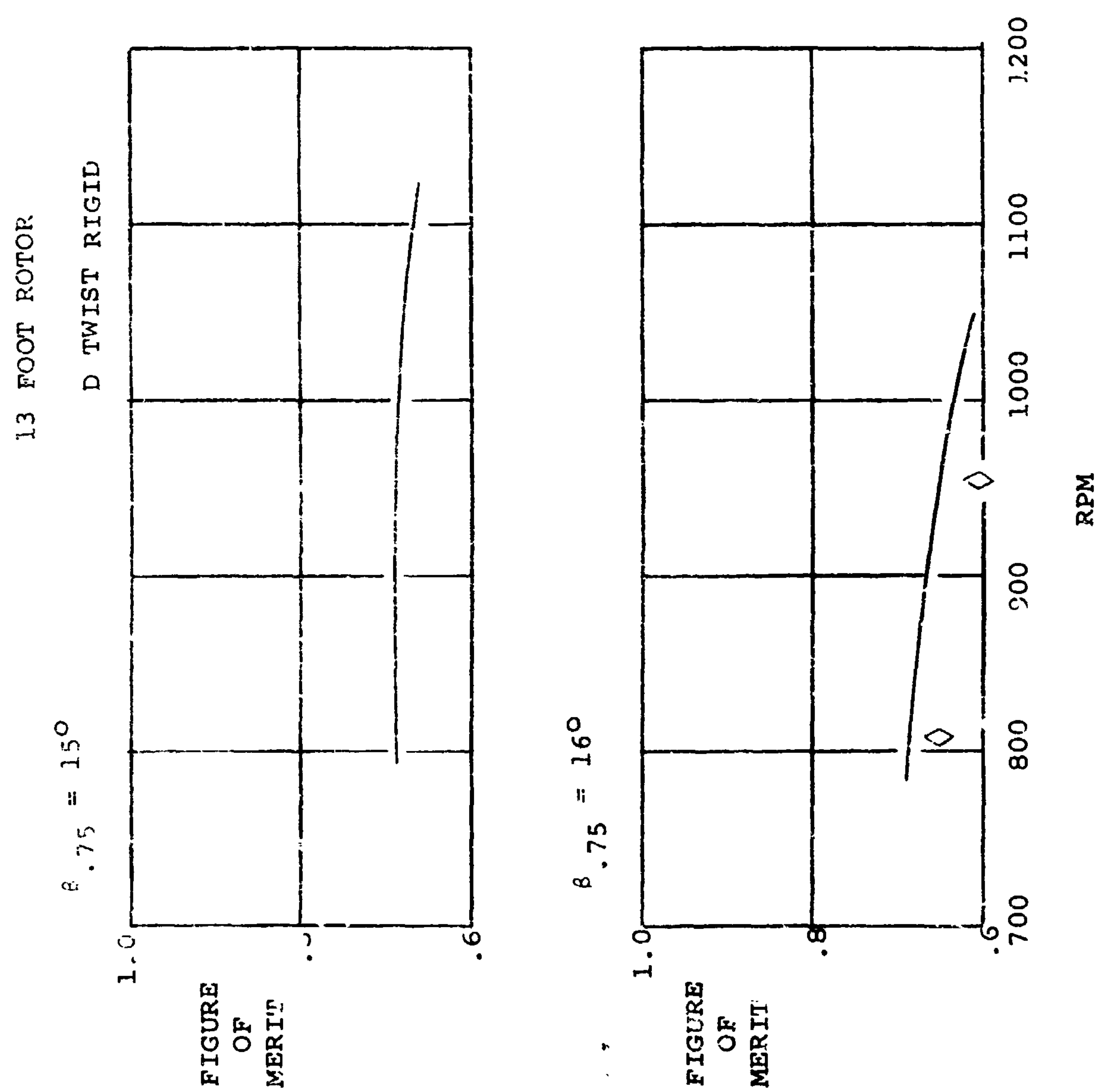

13 FOOT ROTOR
D TWIST RIGID
β .75 = 10°
β .75 = 8°
FIGURE OF MERIT
1.0
.8
.6
FIGURE OF MERIT
1.0
.8
.6
700
800
900
1000
1100
1200
1300
1400
RPM


13 FOOT ROTOR
D TWIST RIGID
β.75 = 11°
β.75 = 12°
FIGURE OF MERIT
1.0
.8
.6
700
800
900
1000
1100
1300
1400
RPM

13 FOOT ROTOR

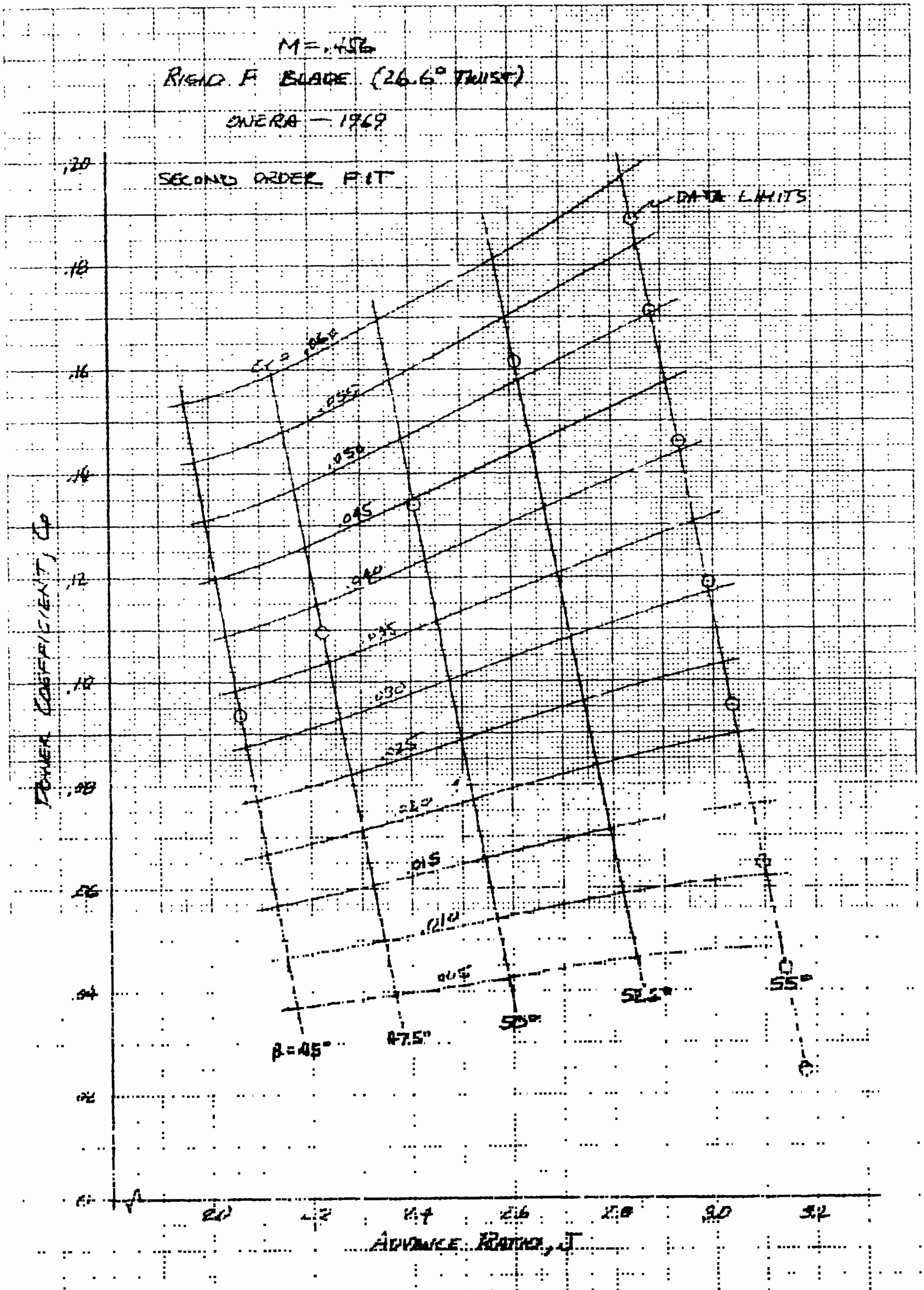
D TWIST RIGID



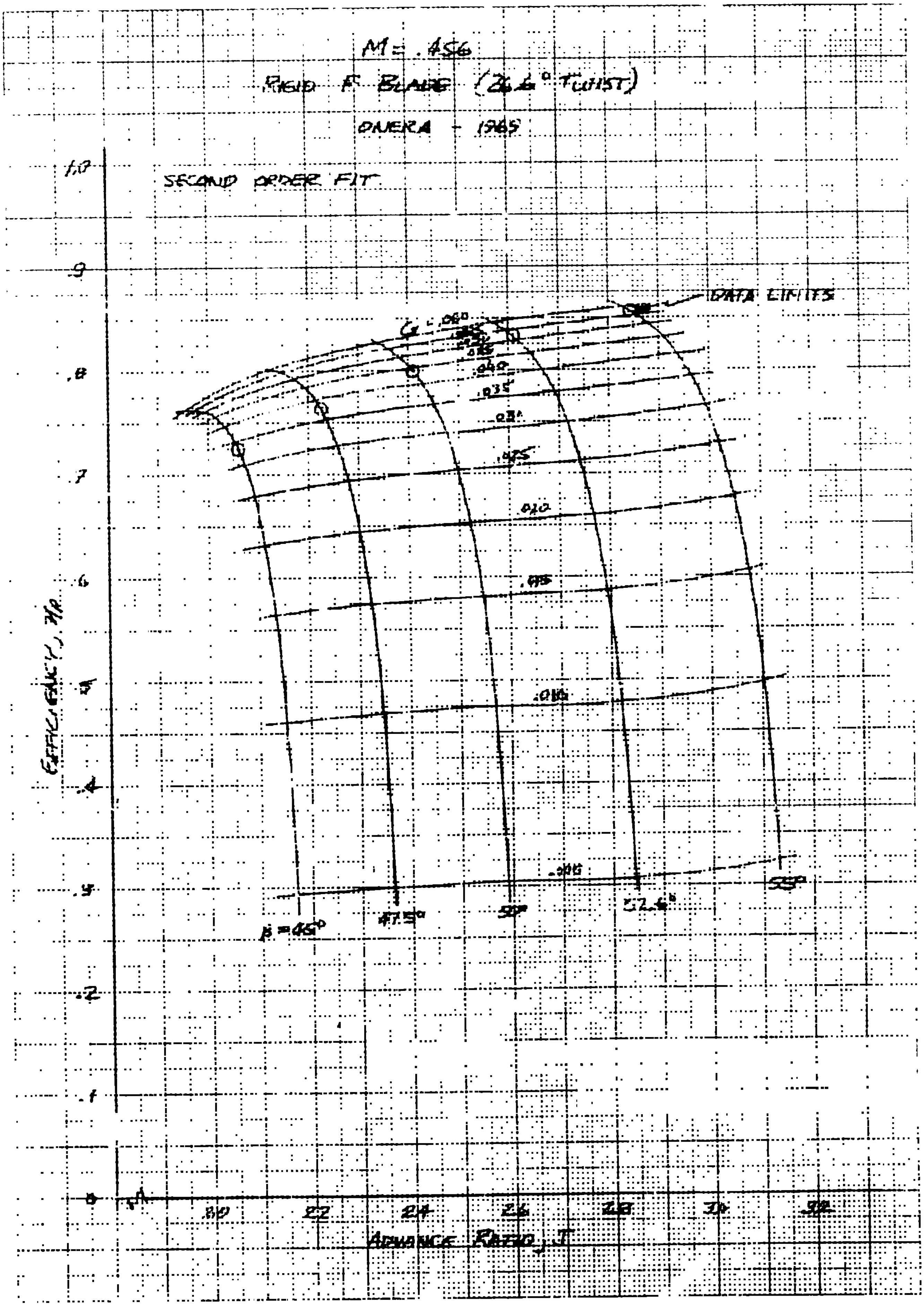

13 FOOT ROTOR
D TWIST RIGID
$\beta_{.75} = 15^{o}$
$\beta_{.75} = 16^{o}$
FIGURE OF MERIT
FIGURE OF MERIT
1.0
.8
.6
700
800
900
1000
1100
1200
RPM

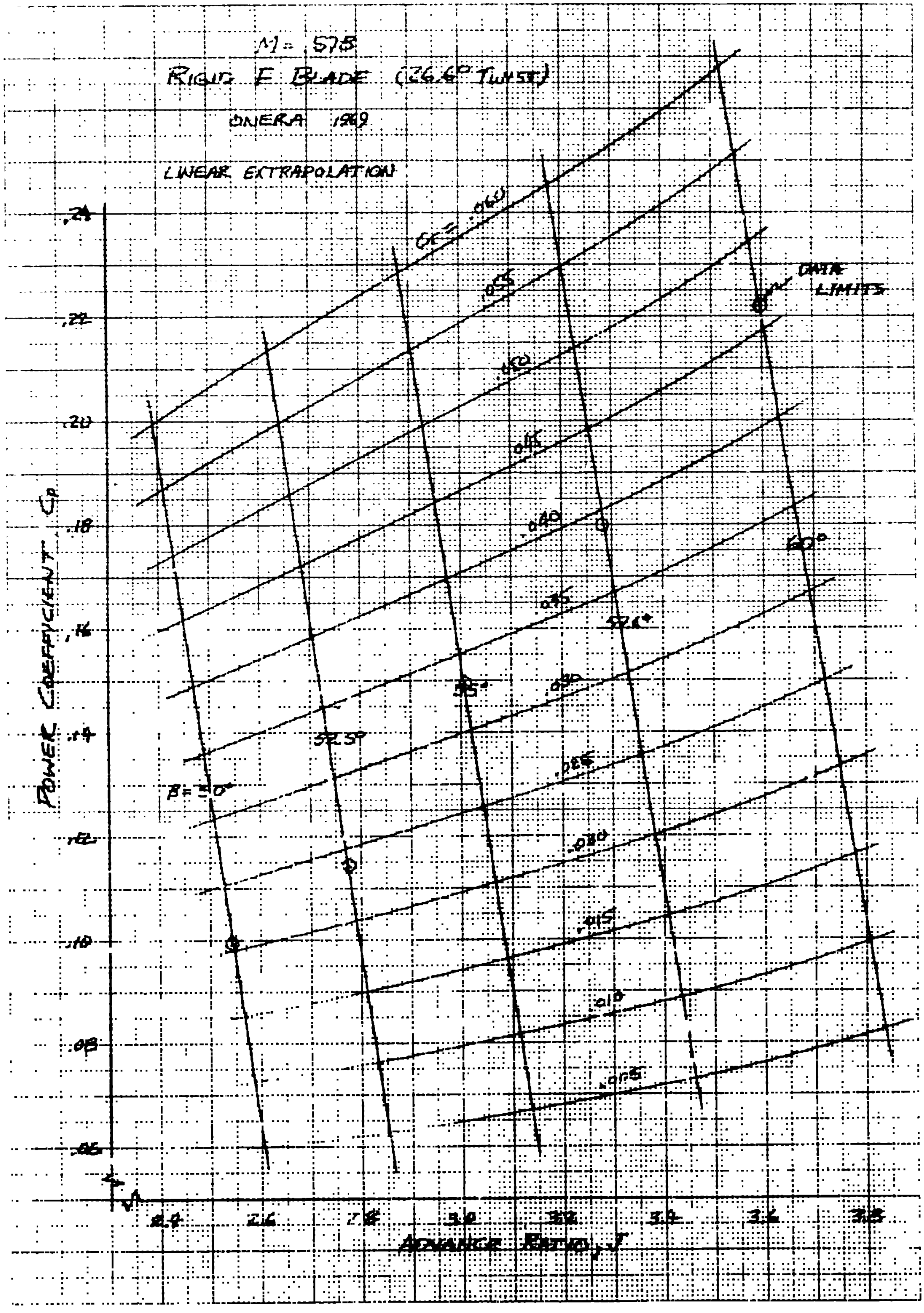
7.0 CRUISE DATA

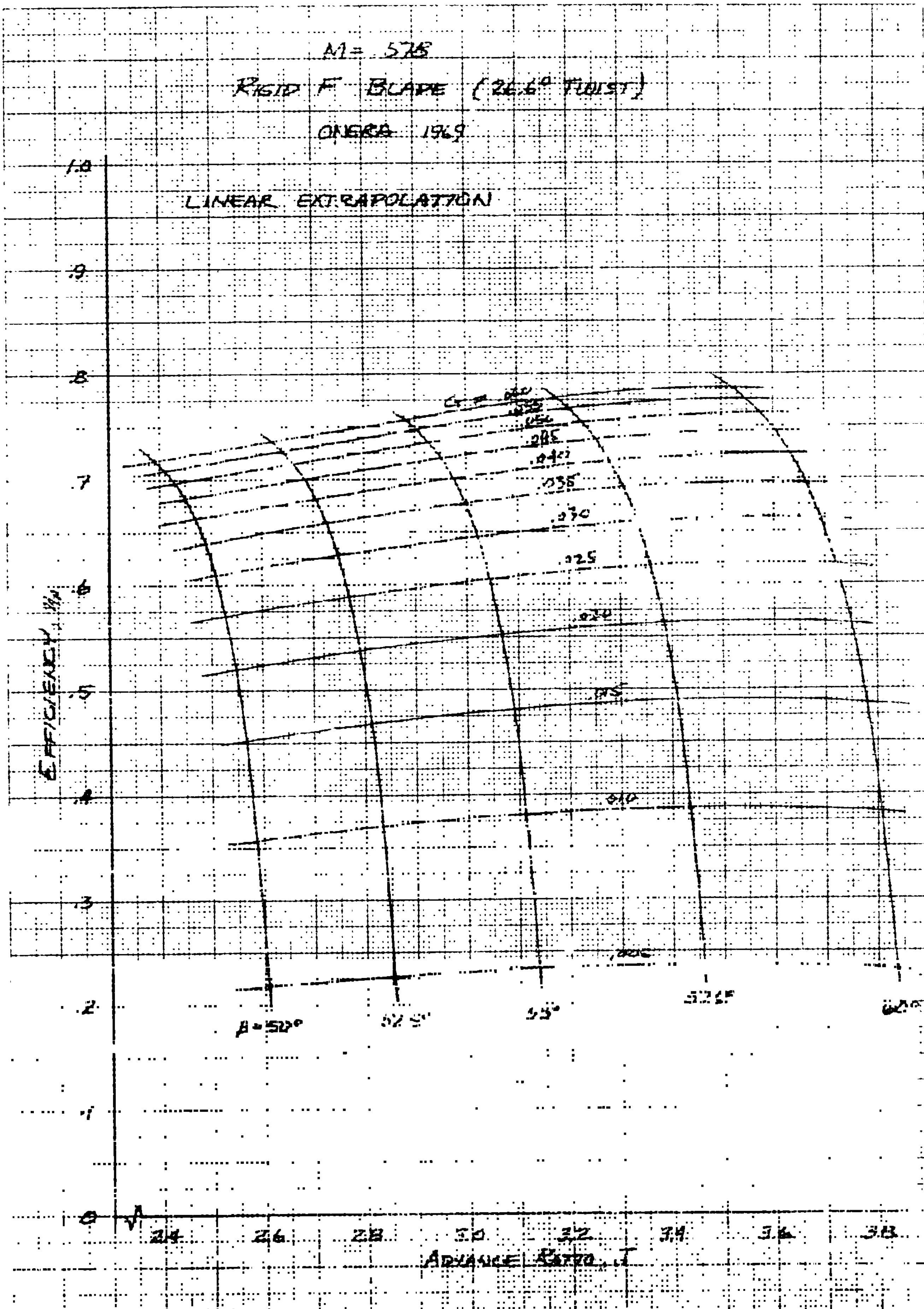
7.1 E BLADE CRUISE DATA



M = .456
RIGID F BLADE (26.6° TWIST)
ONERA — 1969
SECOND ORDER FIT
DATA LIMITS
POWER COEFFICIENT, C_P
ADVANCE RATIO, J
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
0
2.0
2.2
2.4
2.6
2.8
3.0
3.2
.060
.055
.050
.045
.040
.035
.030
.025
.020
.015
.010
.005
β = 45°
47.5°
50°
52.5°
55°


M = .456
RIGID F BLADE (26.6° TWIST)
ONERA - 1965
SECOND ORDER FIT
DATA LIMITS
EFFICIENCY, η_P
ADVANCE RATIO, J
β = 45°
47.5°
50°
52.6°
55°
.010
.015
.020
.025
.030
.035
.040


M = .575
RIGID E BLADE (26.6° TWIST)
ONERA 1969
LINEAR EXTRAPOLATION
C_T = .060
.055
.050
.045
.040
.035
.030
.025
.020
.015
.010
.005
DATA LIMITS
60°
57.5°
55°
52.5°
β = 50°
POWER COEFFICIENT, C_P
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
ADVANCE RATIO, J

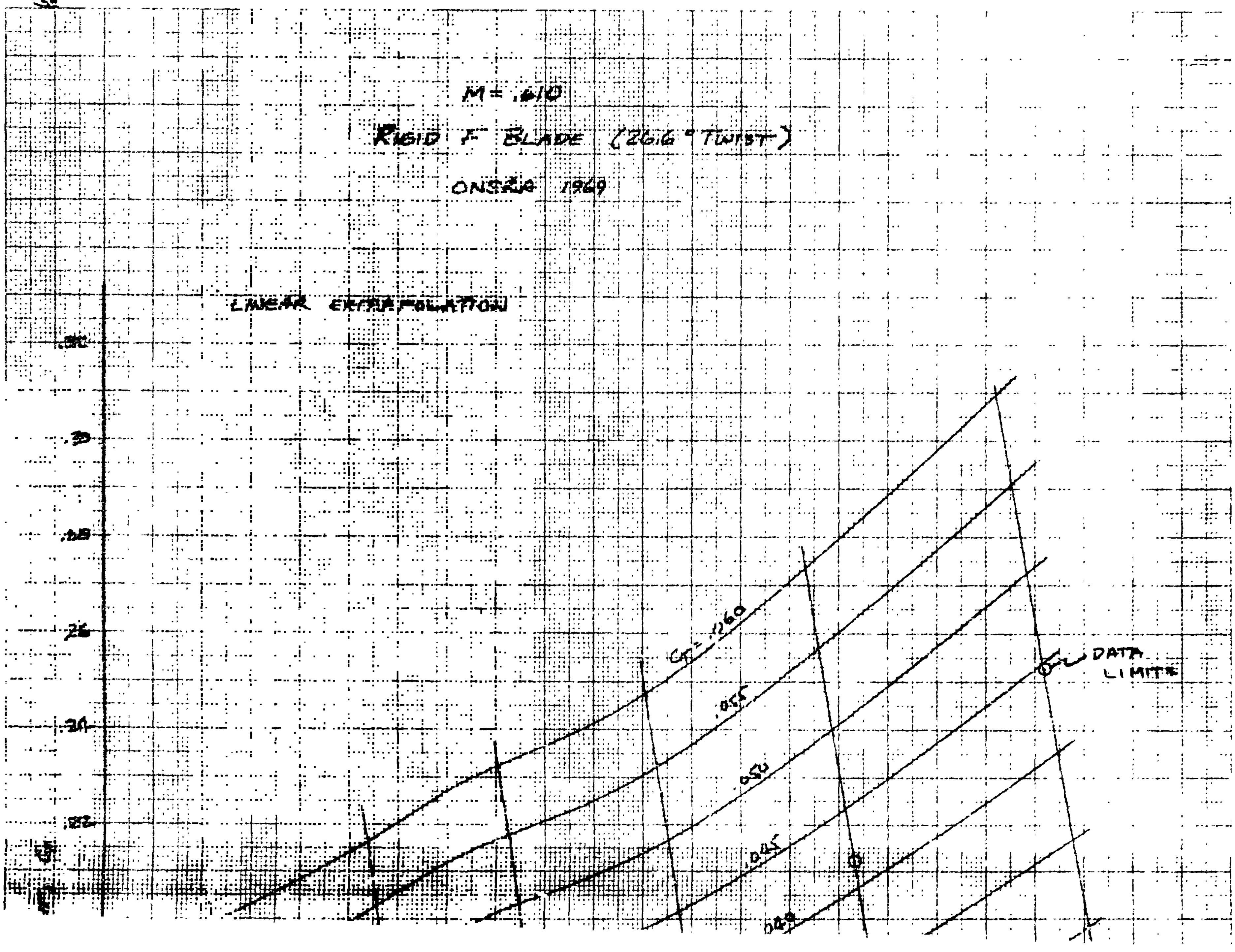

M = .575
RIGID F BLADE (26.6° TWIST)
ONERA 1969
LINEAR EXTRAPOLATION
EFFICIENCY, η
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
C_T = .060
.055
.050
.045
.040
.035
.030
.025
.020
.015
.010
.005
β = 50°
52.5°
55°
57.5°
60°
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
ADVANCE RATIO, J

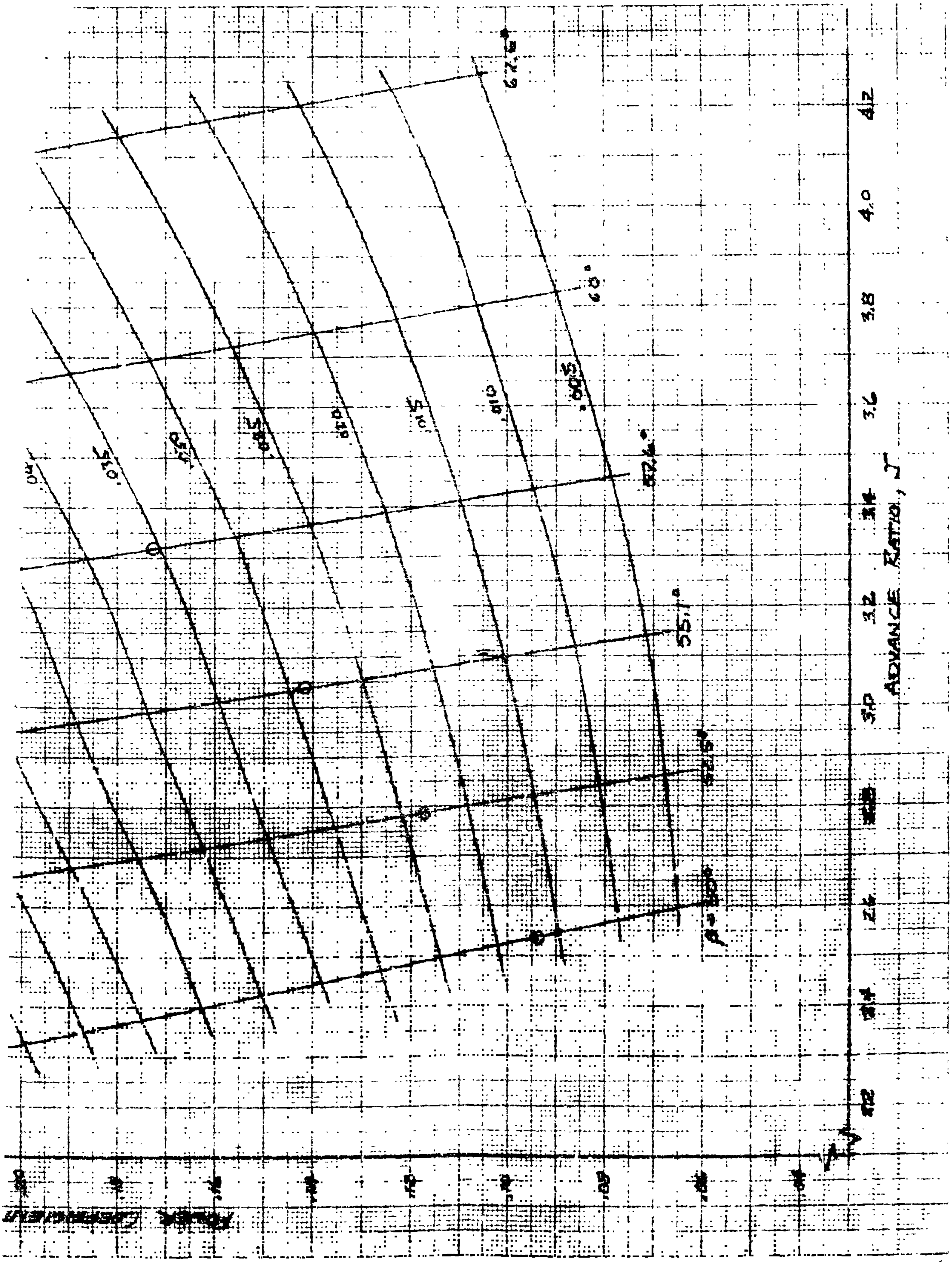
FOLDOUT FRAME

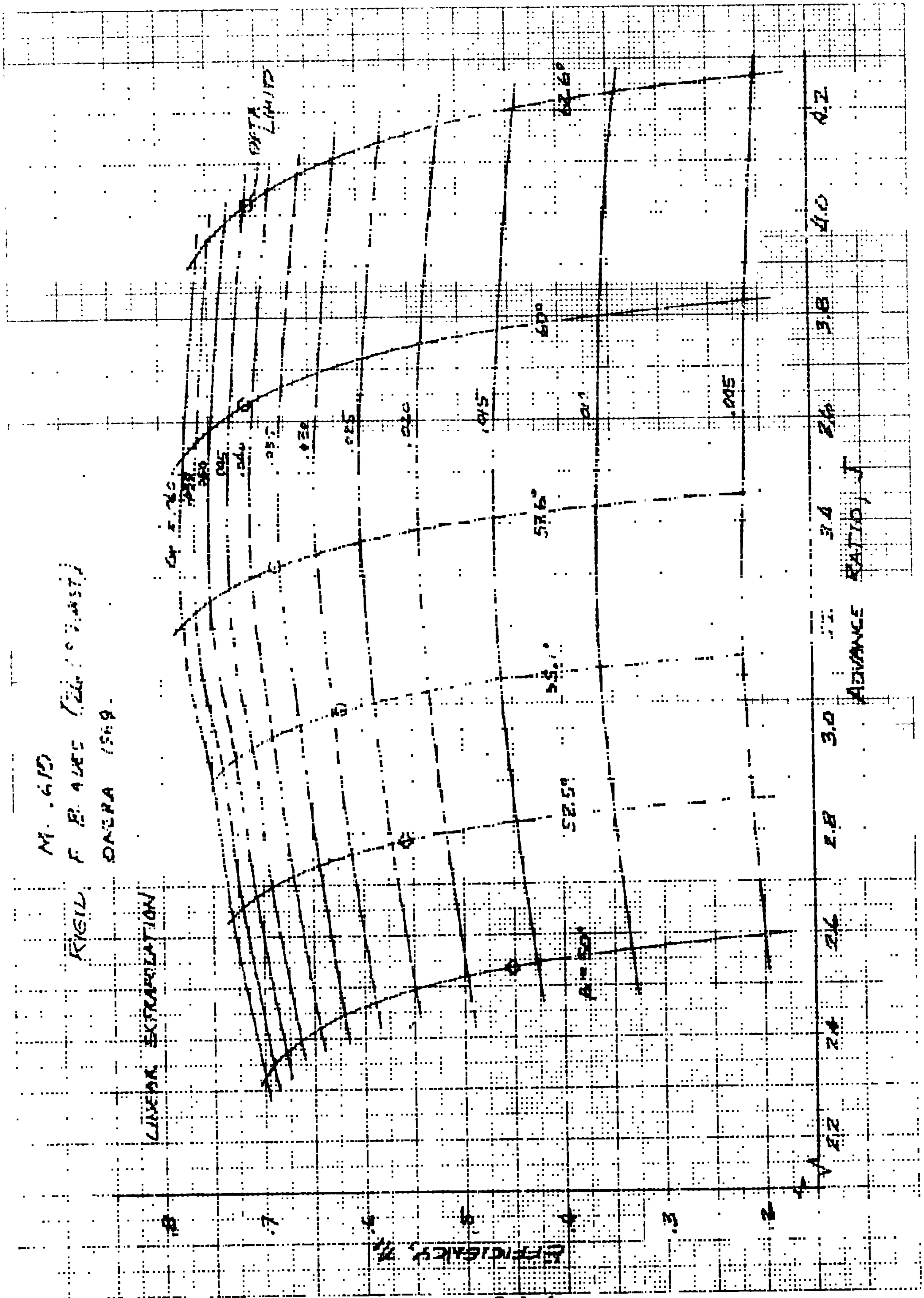
NO. 340DR MP DIETZGEN GRAPH PAPER
MILLIMETER

EUGENE DIETZGEN CO.

THE BOEING COMPANY

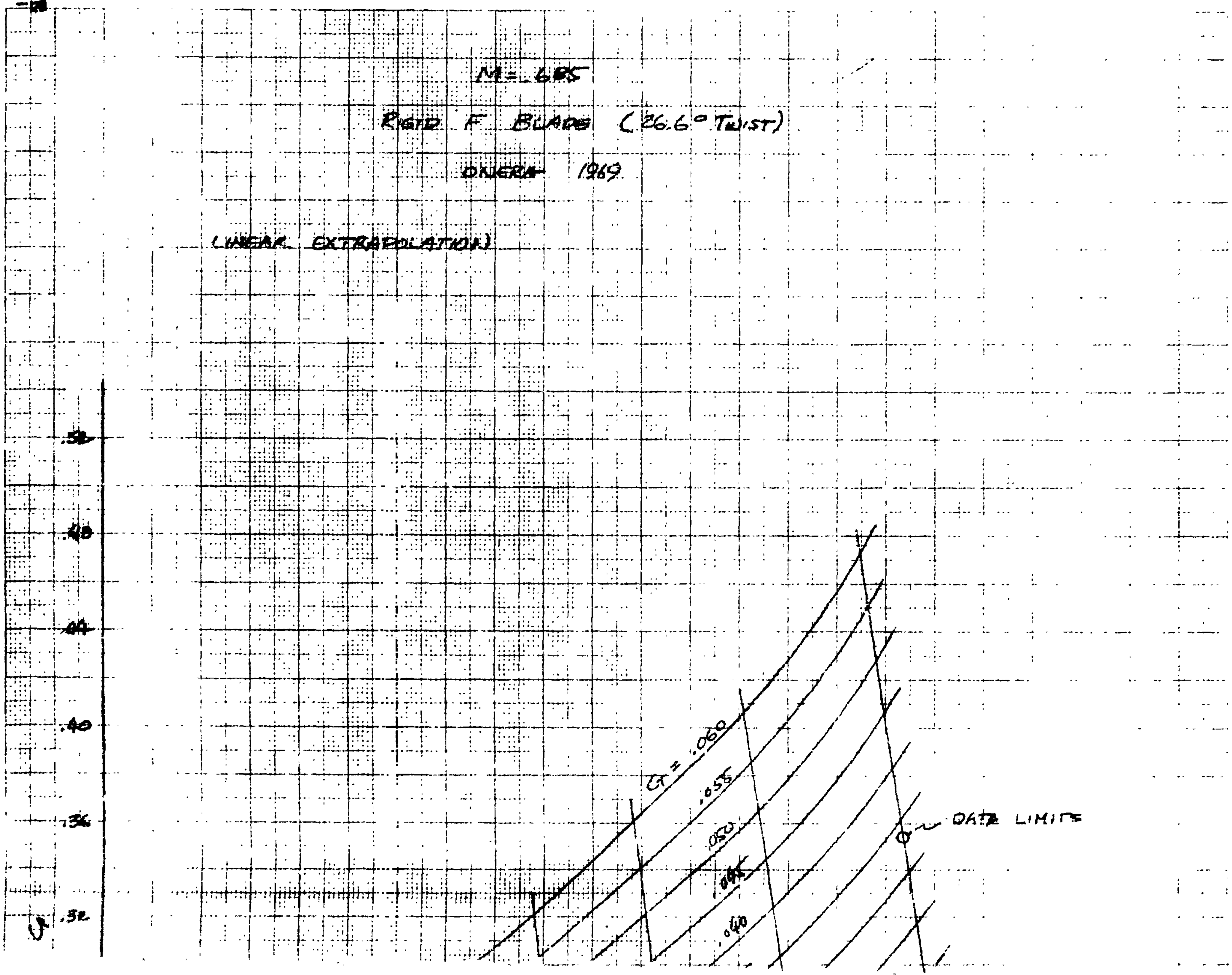


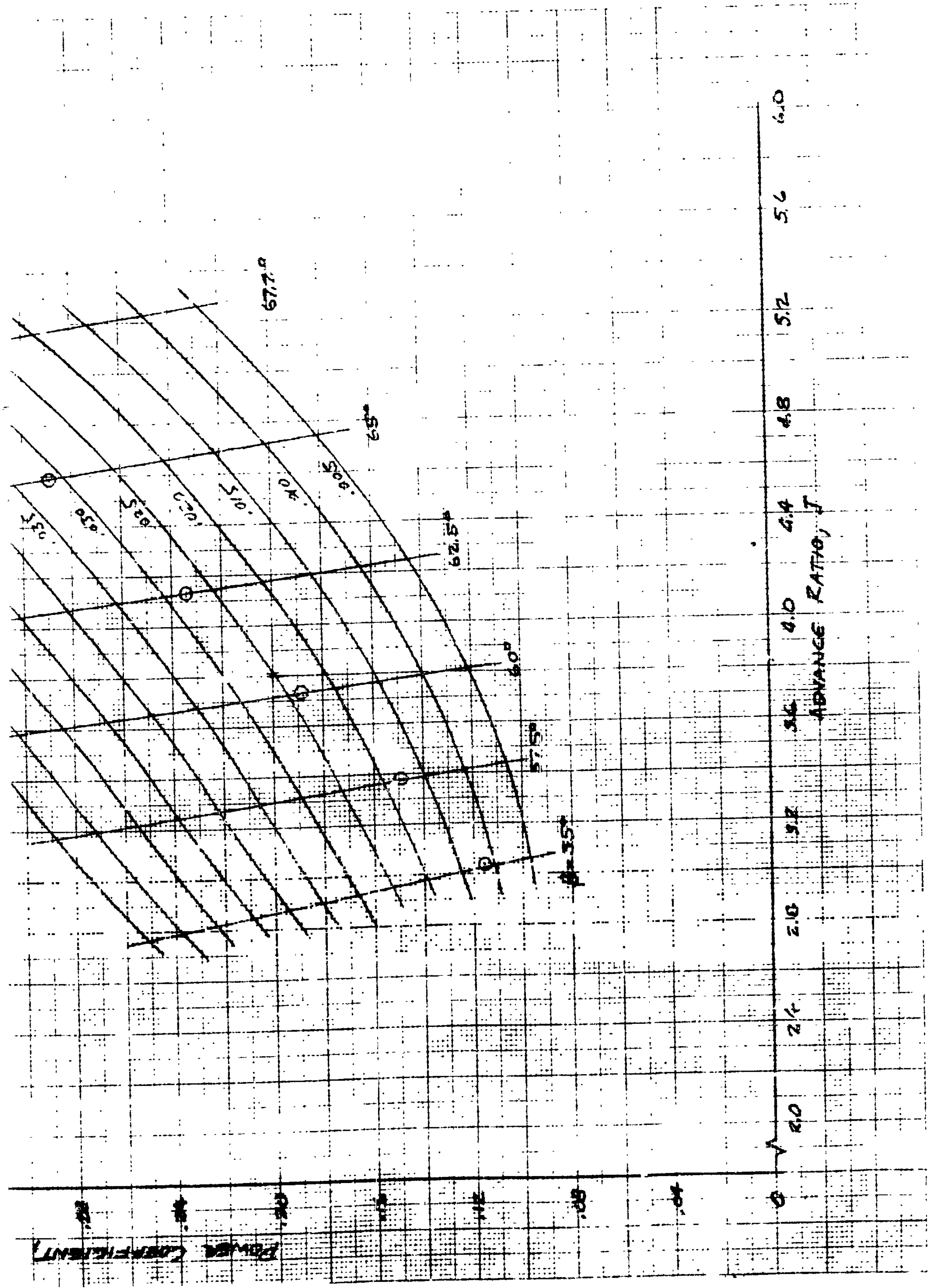

ADVANCE RATIO, J
4.0
3.8
3.6
3.2
3.0
60°
55.1°

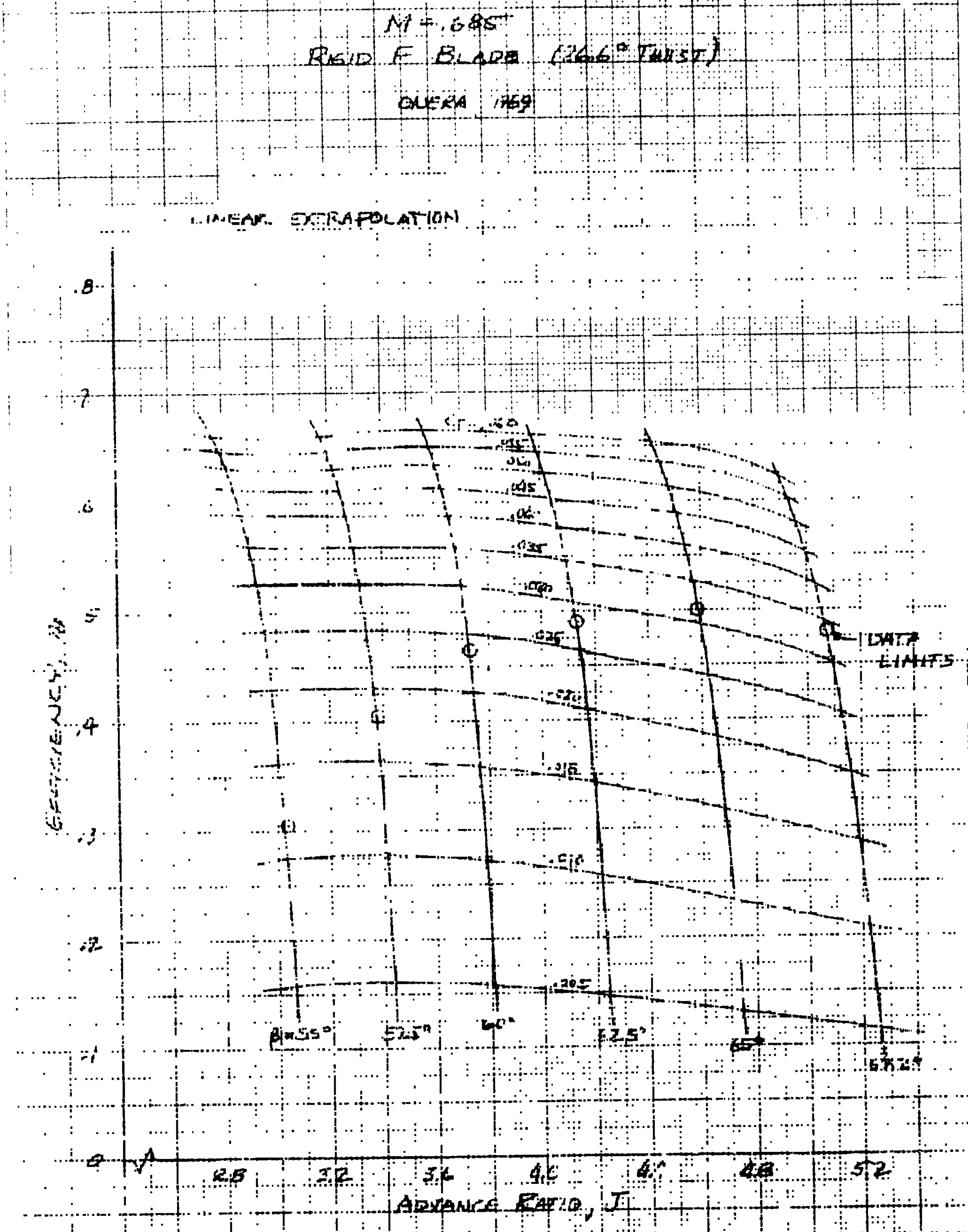

LINEAR EXTRAPOLATION
DATA LIMIT
ADVANCE RATIO, J
EFFICIENCY, %
β = 50°
52.5°
57.6°
60°
62.6°
2.2
2.4
2.6
2.8
3.0
3.4
3.6
3.8
4.0
4.2
.2
.3
.4
.5
.6
.7
.8

FOLDOUT FRAME

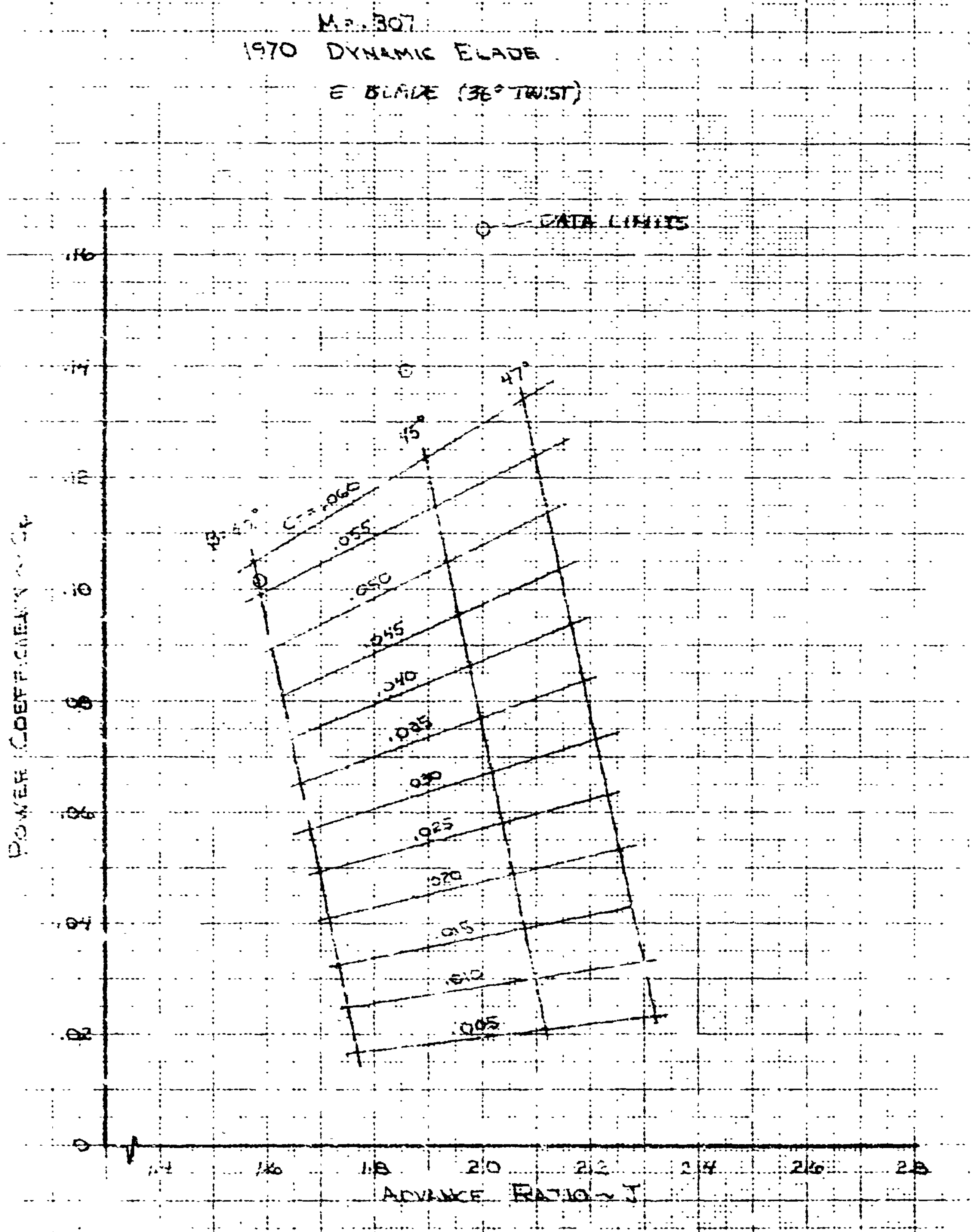
THE BOEING COMPANY

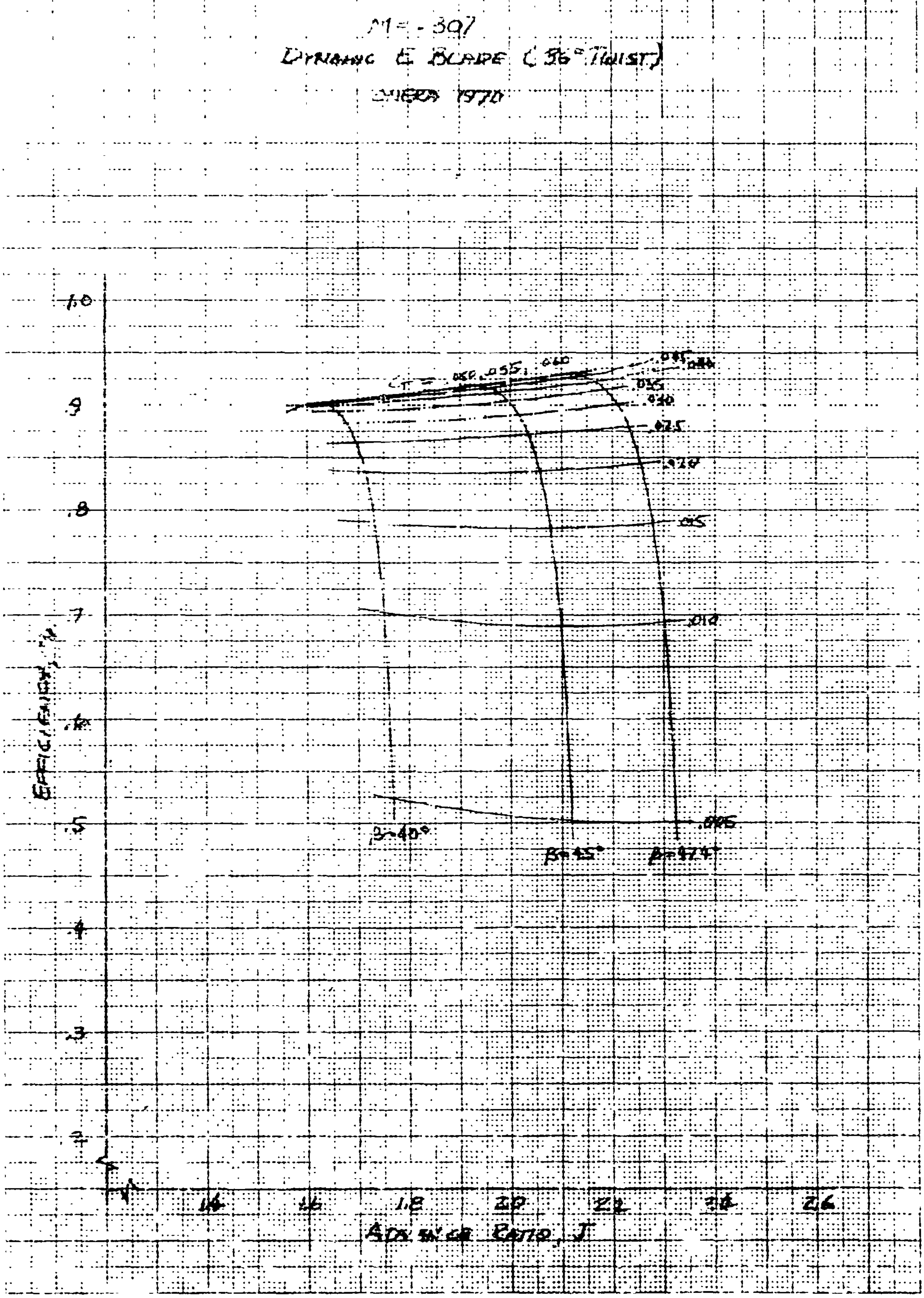


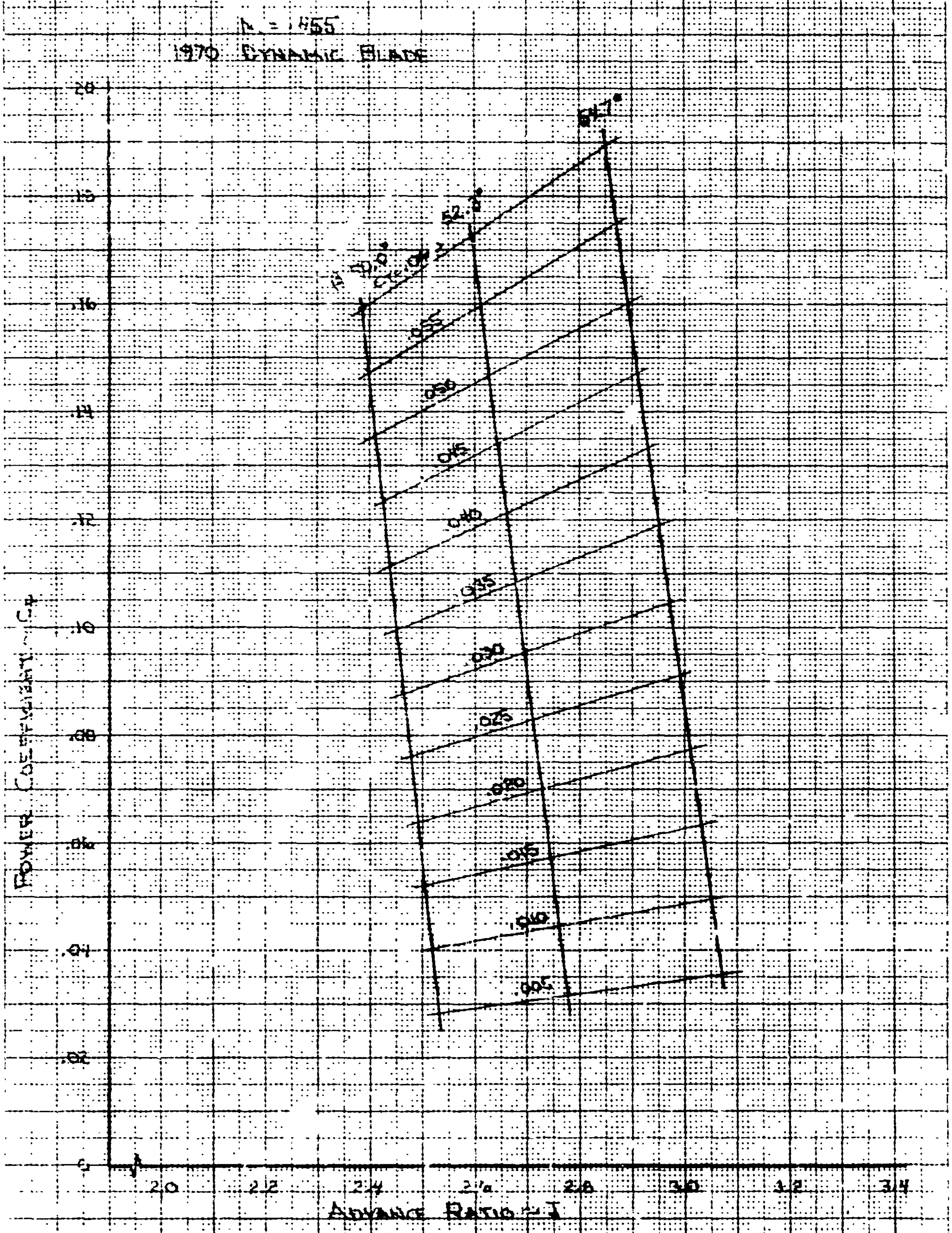

ADVANCE RATIO, J
POWER COEFFICIENT
67.5°
65°
62.5°
60°
57.5°
55°
.005
.010
.015
.020
.025
.030
.035
6.0
5.6
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
.04
.08
.12
.16
.20
.24
.28
0


M = .685
RIGID F BLADE (26.6° TWIST)
ONERA 1969
LINEAR EXTRAPOLATION
DATA LIMITS
β=55°
57.5°
60°
62.5°
65°
67.5°
EFFICIENCY, η
ADVANCE RATIO, J

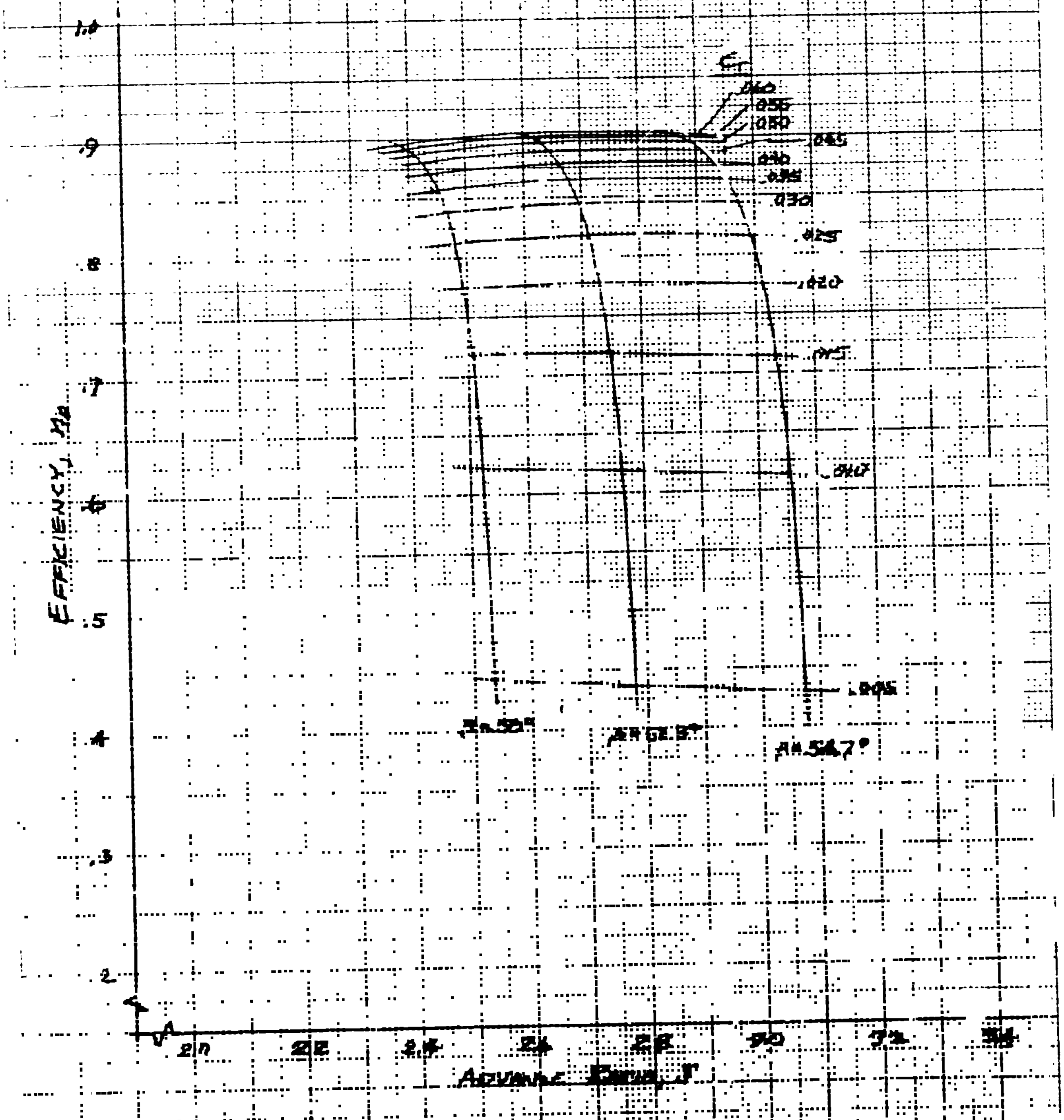
7.2 E BLADES CRUISE DATA

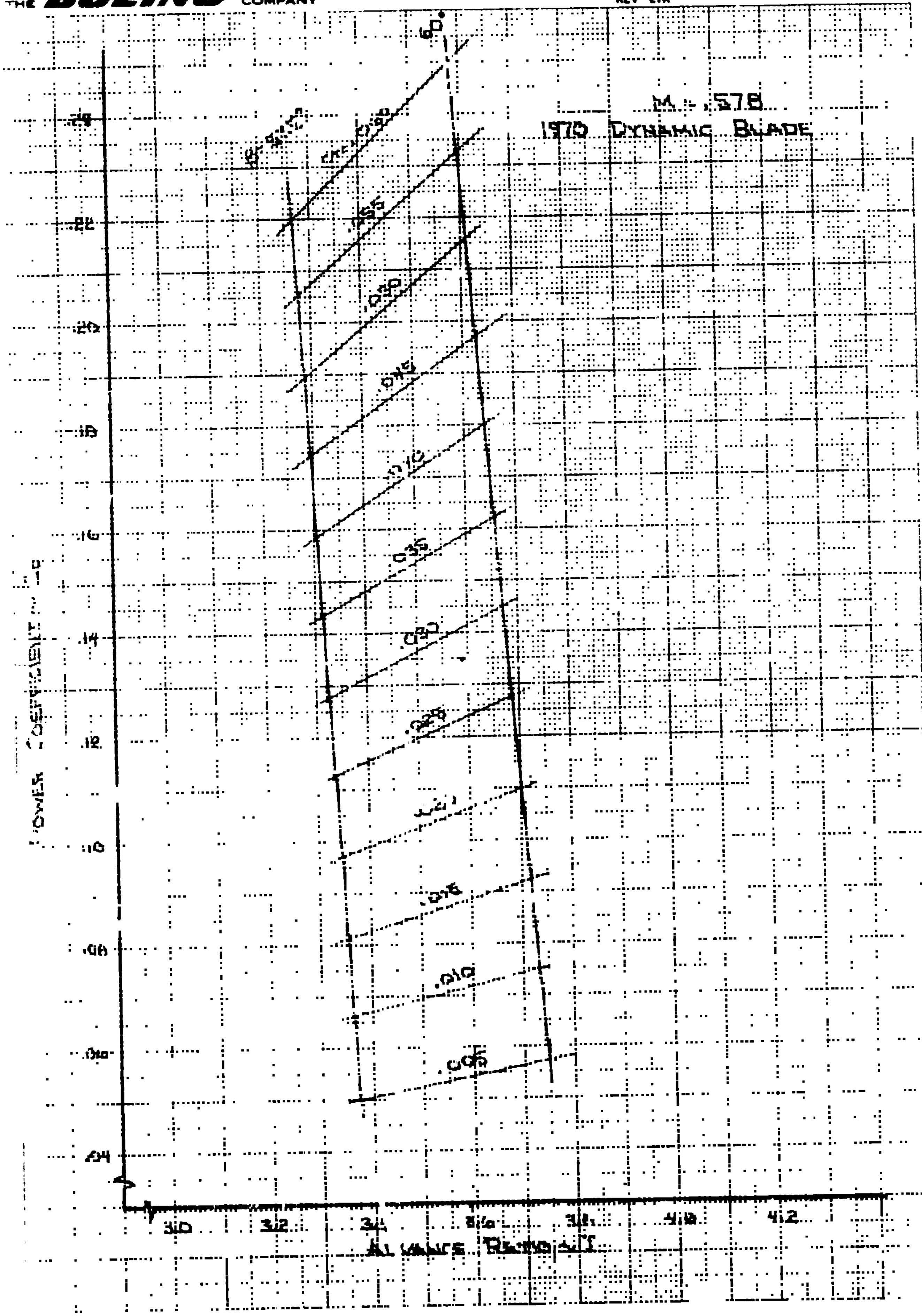

M.. 307
1970 DYNAMIC BLADE
E BLADE (36° TWIST)
DATA LIMITS
POWER COEFFICIENT ~ CP
ADVANCE RATIO ~ J
47°
45°
C = .060
.055
.050
.045
.040
.035
.030
.025
.020
.015
.010
.005
.16
.14
.12
.10
.08
.06
.04
.02
0
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8

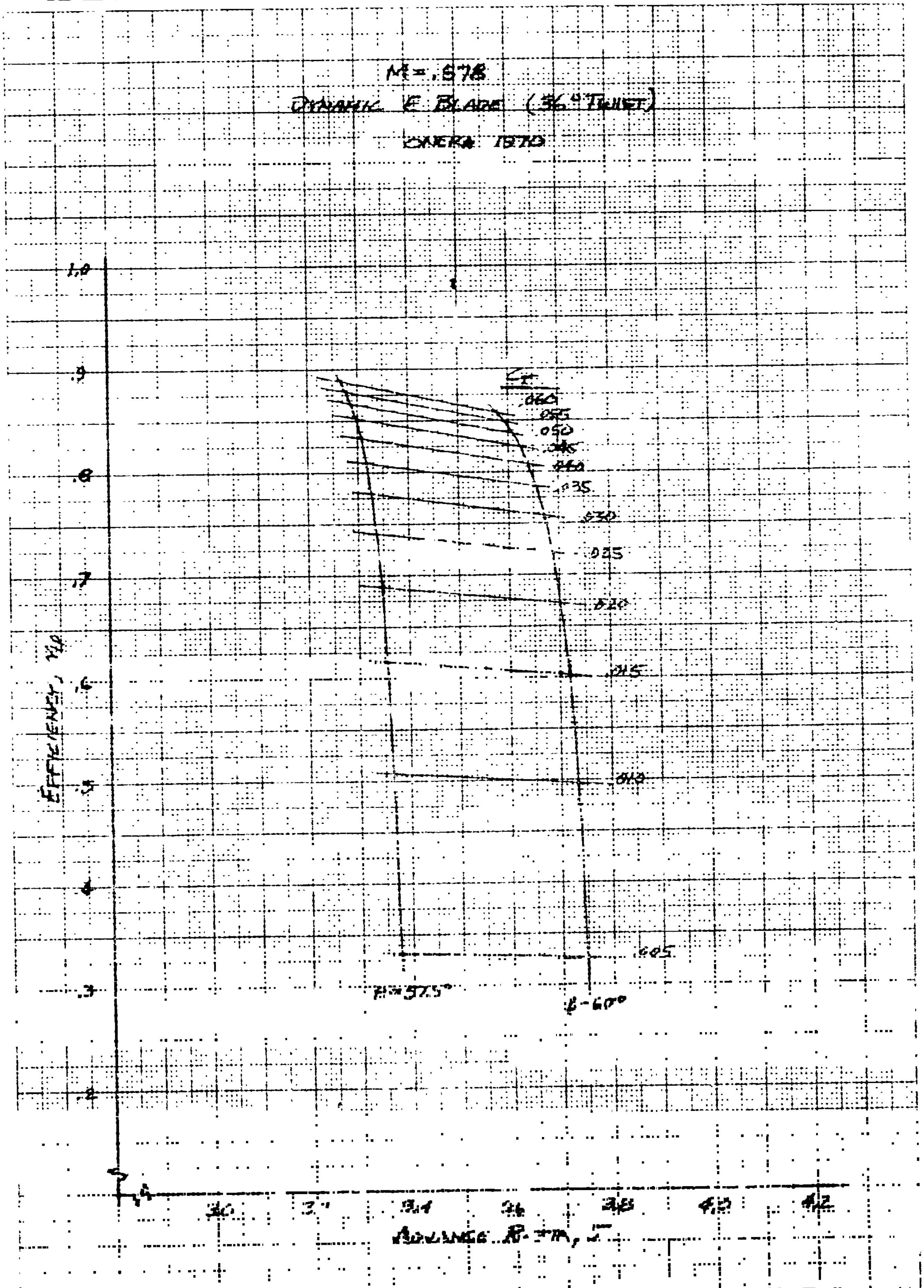

M = .307
DYNAMIC E BLADE (56° TWIST)
1970
1.0
.9
.8
.7
.6
.5
.4
.3
.2
EFFICIENCY
C_T = .050 .055 .060
.035
.030
.025
.020
.015
.010
.005
β=40°
β=45°
β=47½°
1.8
2.0
ADVANCE RATIO, J

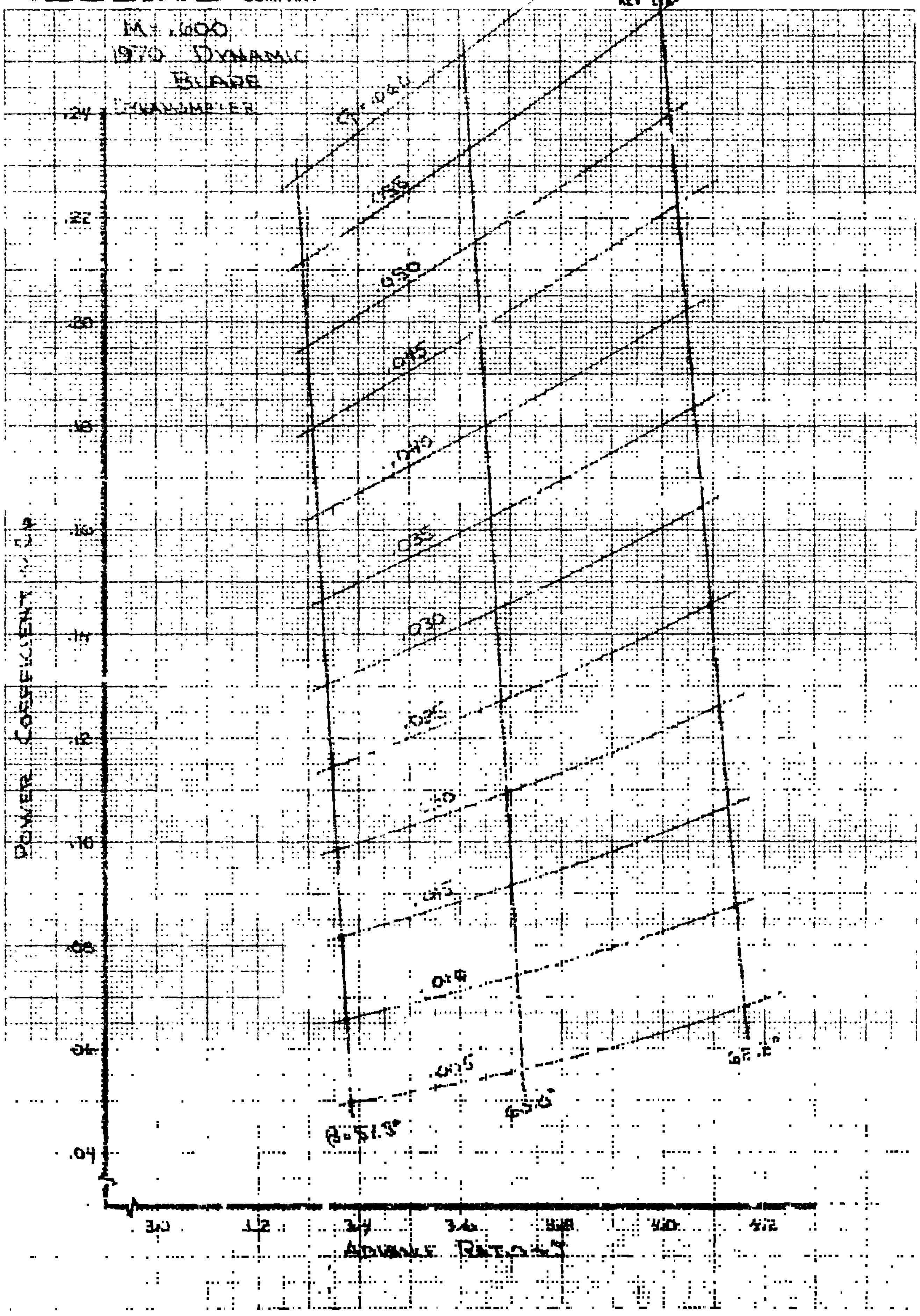

M = .455
1970 DYNAMIC BLADE
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
0
57°
52.2°
.055
.050
.045
.040
.035
.030
.025
.020
.015
.010
.005
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
POWER COEFFICIENT - C_P
ADVANCE RATIO - J

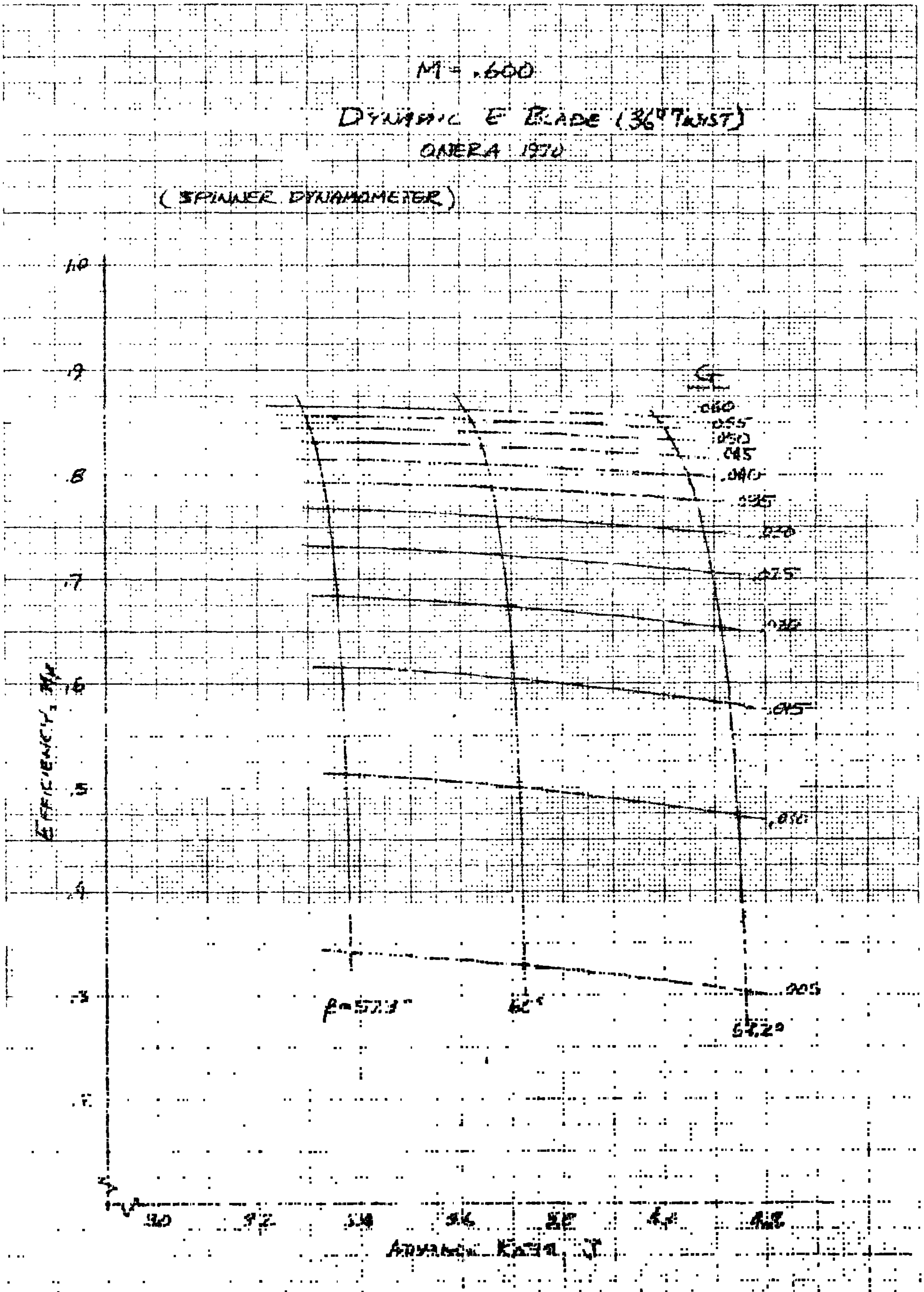
M = .455
Dynamic G Blade (36° Twist)
1970

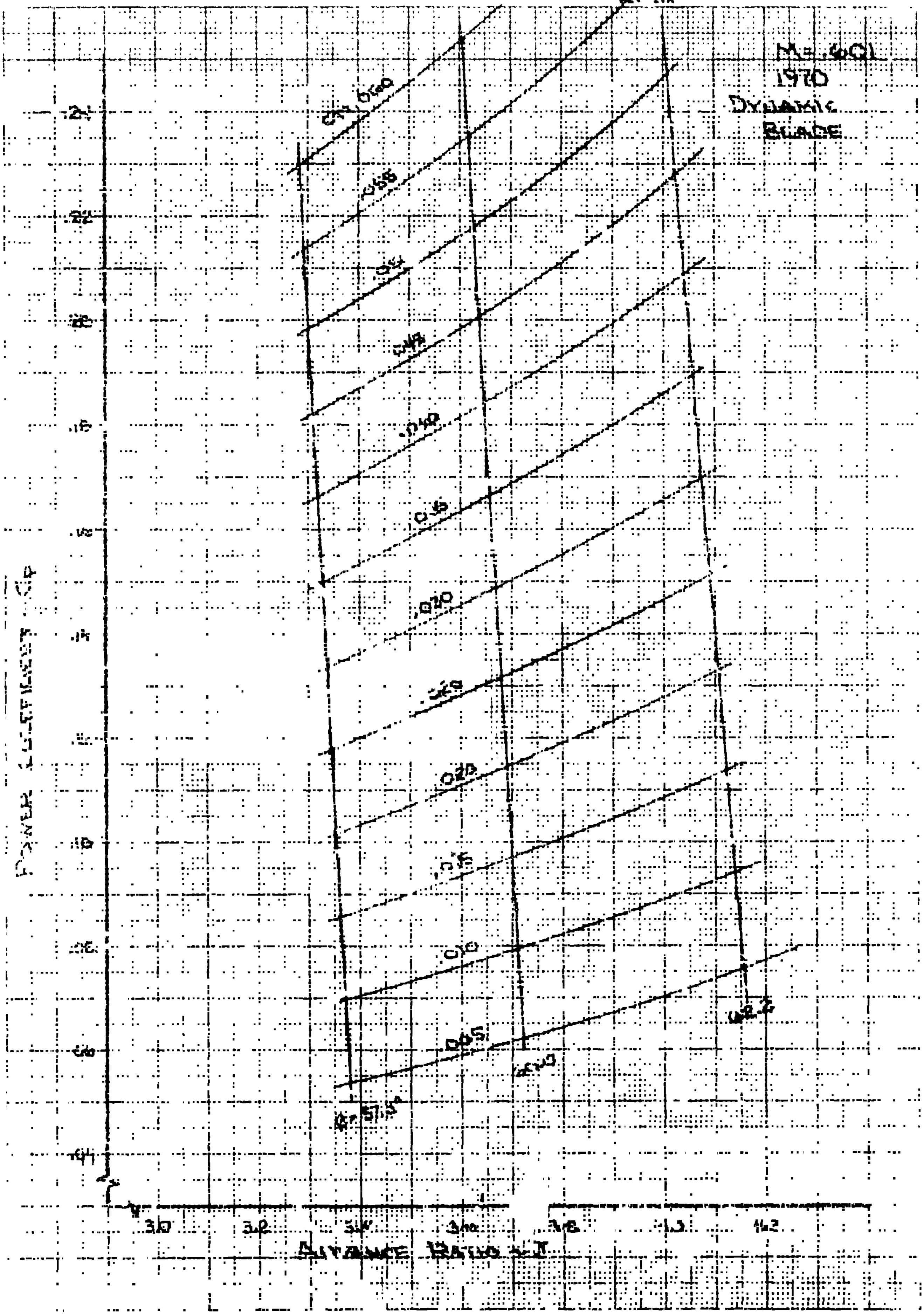


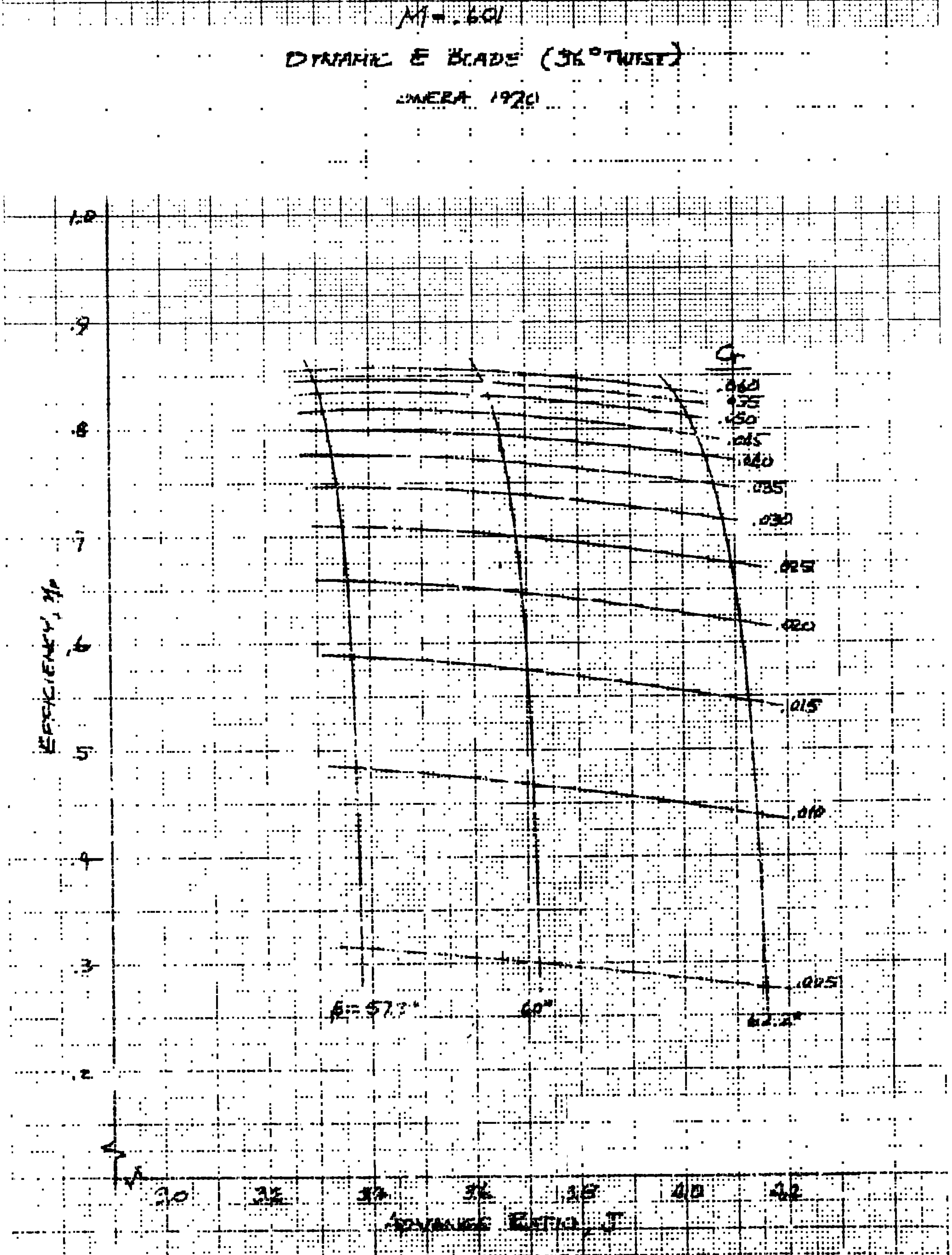

M = .578
1975 DYNAMIC BLADE
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
.055
.050
.045
.040
.035
.030
.025
.020
.015
.010
.005
POWER COEFFICIENT ~ C_P
3.0
3.2
3.4
3.6
3.8
4.0
4.2


M = .578
Dynamic E Blade (36° Twist)
ONERA 1970
C_P
.060
.055
.050
.045
.040
.035
.030
.025
.020
.015
.010
.005
β = 57.5°
β = 60°
Efficiency, η_P
1.0
.9
.8
.7
.6
.5
.4
.3
.2
Advance Ratio, J


1970 DYNAMIC
BLADE
POWER COEFFICIENT
ADVANCE RATIO

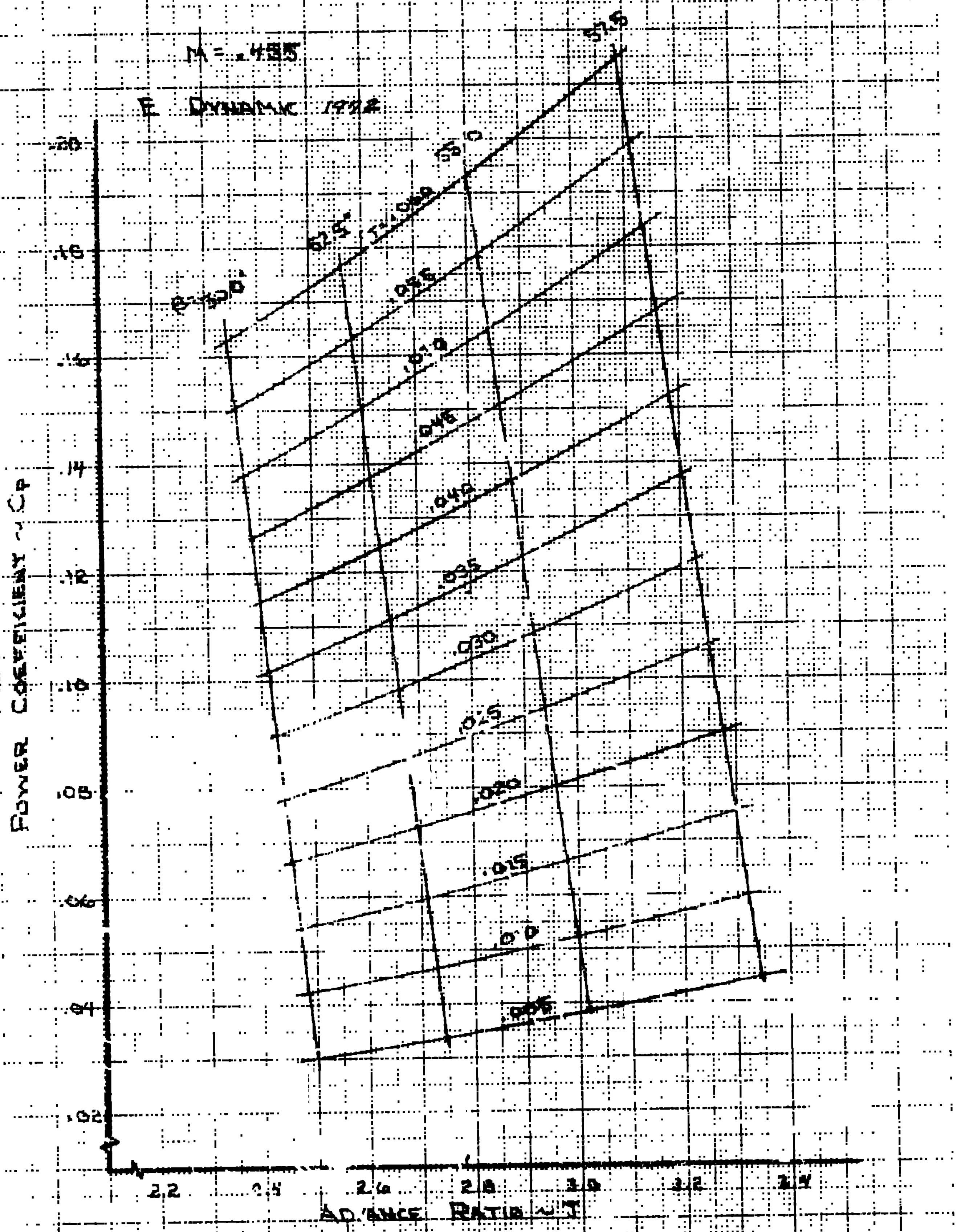

M = .600
DYNAMIC E BLADE (36° TWIST)
ONERA 1970
(SPINNER DYNAMOMETER)
G
.060
.055
.050
.045
.040
.035
.030
.025
.020
.015
.010
.005
β=57.3°
62°
67.2°
EFFICIENCY, η_M
1.0
.9
.8
.7
.6
.5
.4
.3
.2
ADVANCE RATIO, J

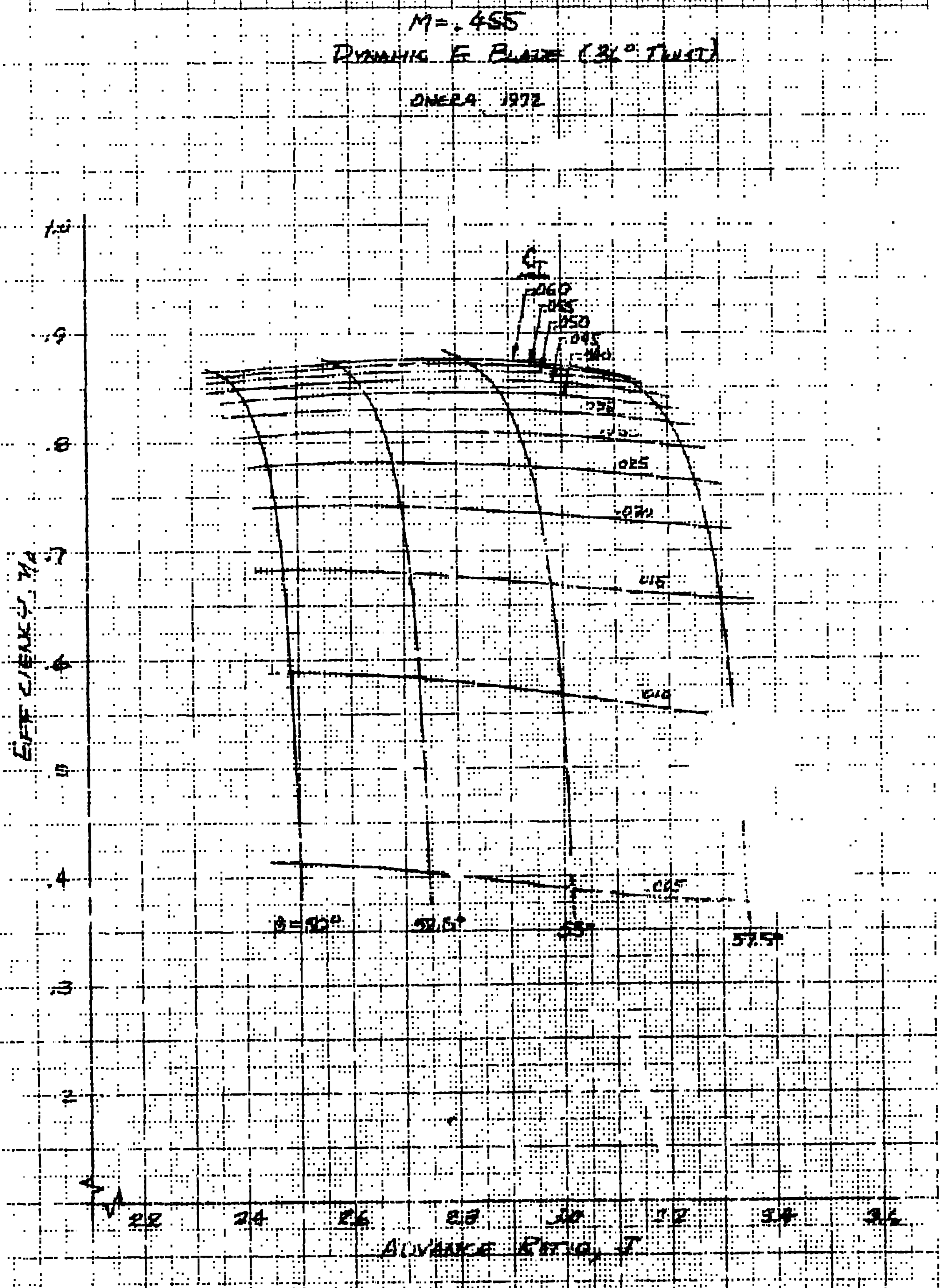

M=.601
1970
Dynamic
Blade
POWER COEFFICIENT - CP
ADVANCE RATIO - J
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
3.0
3.2
3.4
3.6
3.8
4.0
4.2
CT = .060
.055
.050
.045
.040
.035
.030
.025
.020
.015
.010
.005
β=57.5°
62.5


M = .601
DYNAMIC E BLADE (36° TWIST)
ONERA 1920
EFFICIENCY, η_p
ADVANCE RATIO, J
C_P
.060
.055
.050
.045
.040
.035
.030
.025
.020
.015
.010
.005
β = 57.7°
60°
62.2°
1.0
.9
.8
.7
.6
.5
.4
.3
.2
3.0
3.2
3.4
3.6
3.8
4.0
4.2

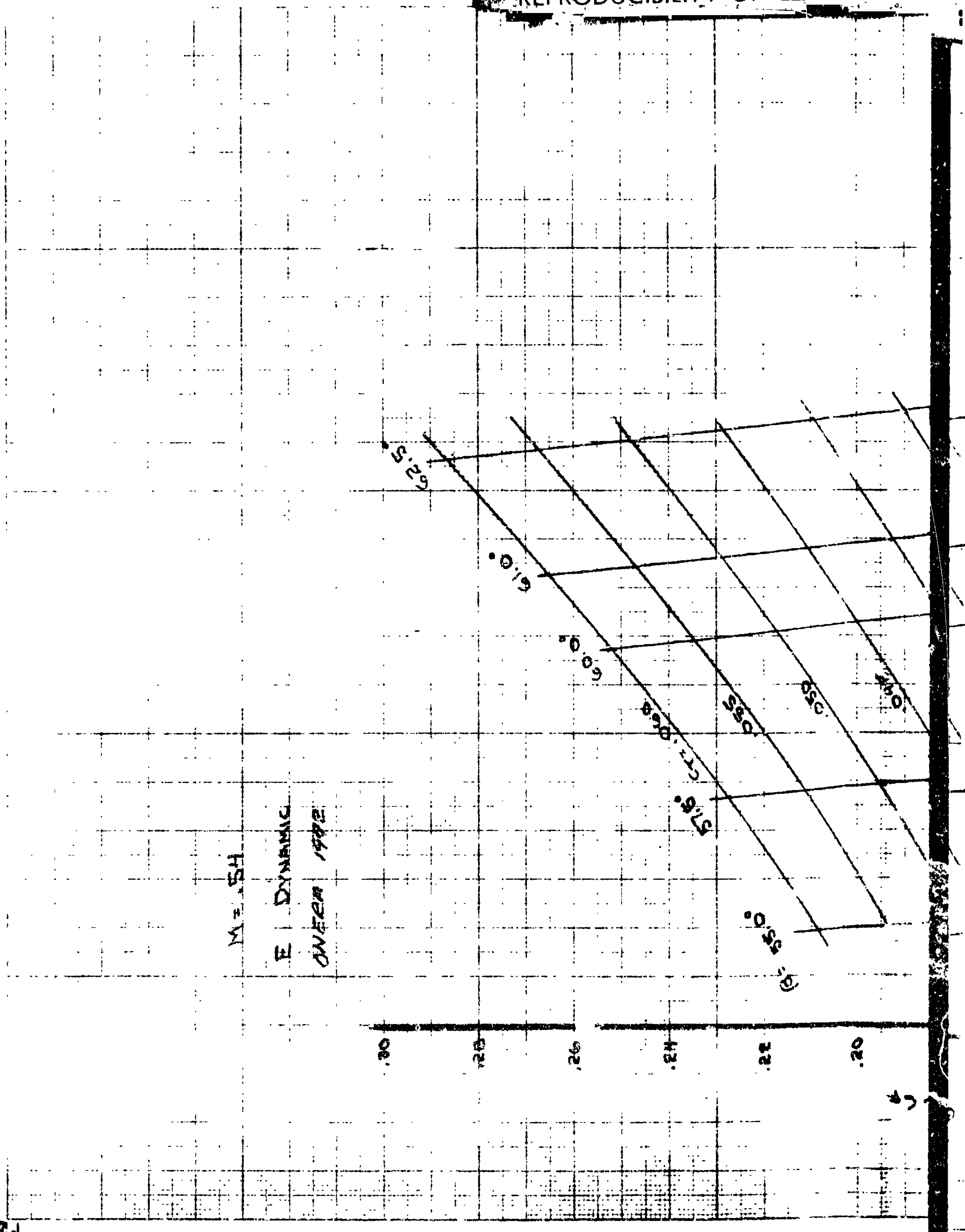
THE BOEING COMPANY

NUMBER D160-10021-1
REV LTR



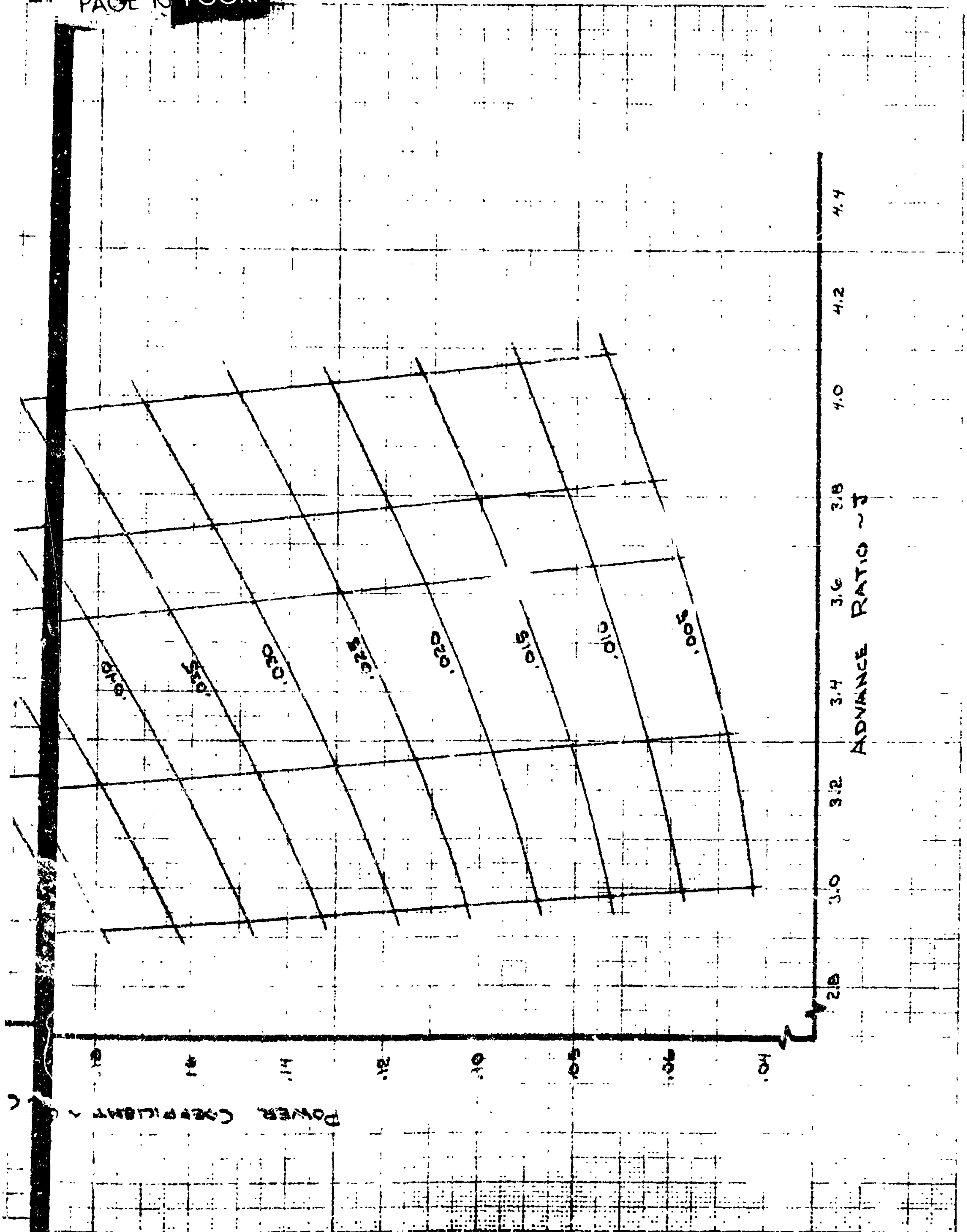

M = .455
DYNAMIC E BLADE (34° TWIST)
ONERA 1972
C_T
.060
.055
.050
.045
.040
.035
.030
.025
.020
.015
.010
.005
β = 50°
52.5°
55°
57.5°
1.0
.9
.8
.7
.6
.5
.4
.3
.2
EFFICIENCY, η_p
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
ADVANCE RATIO, J

THE BOEING COMPANY

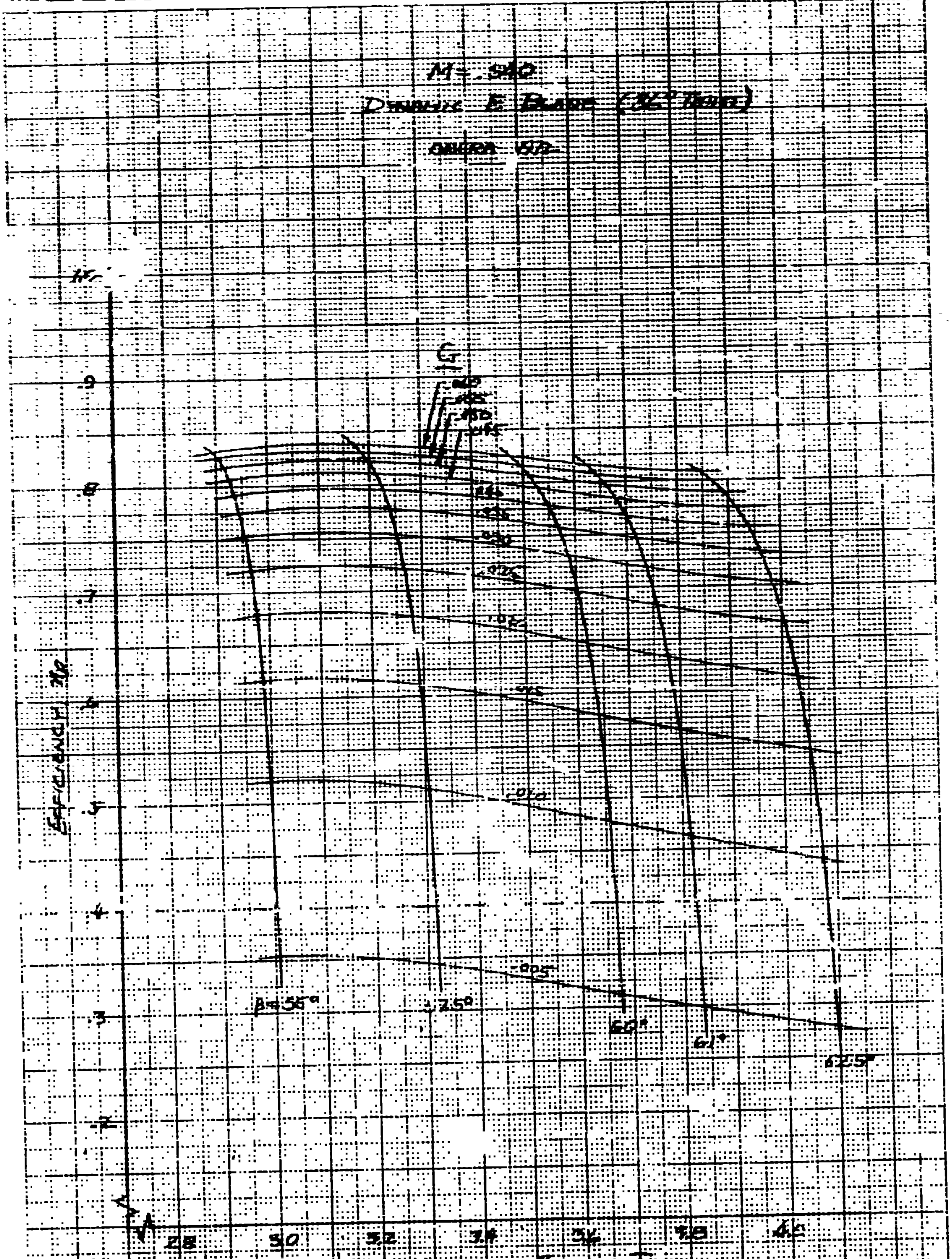


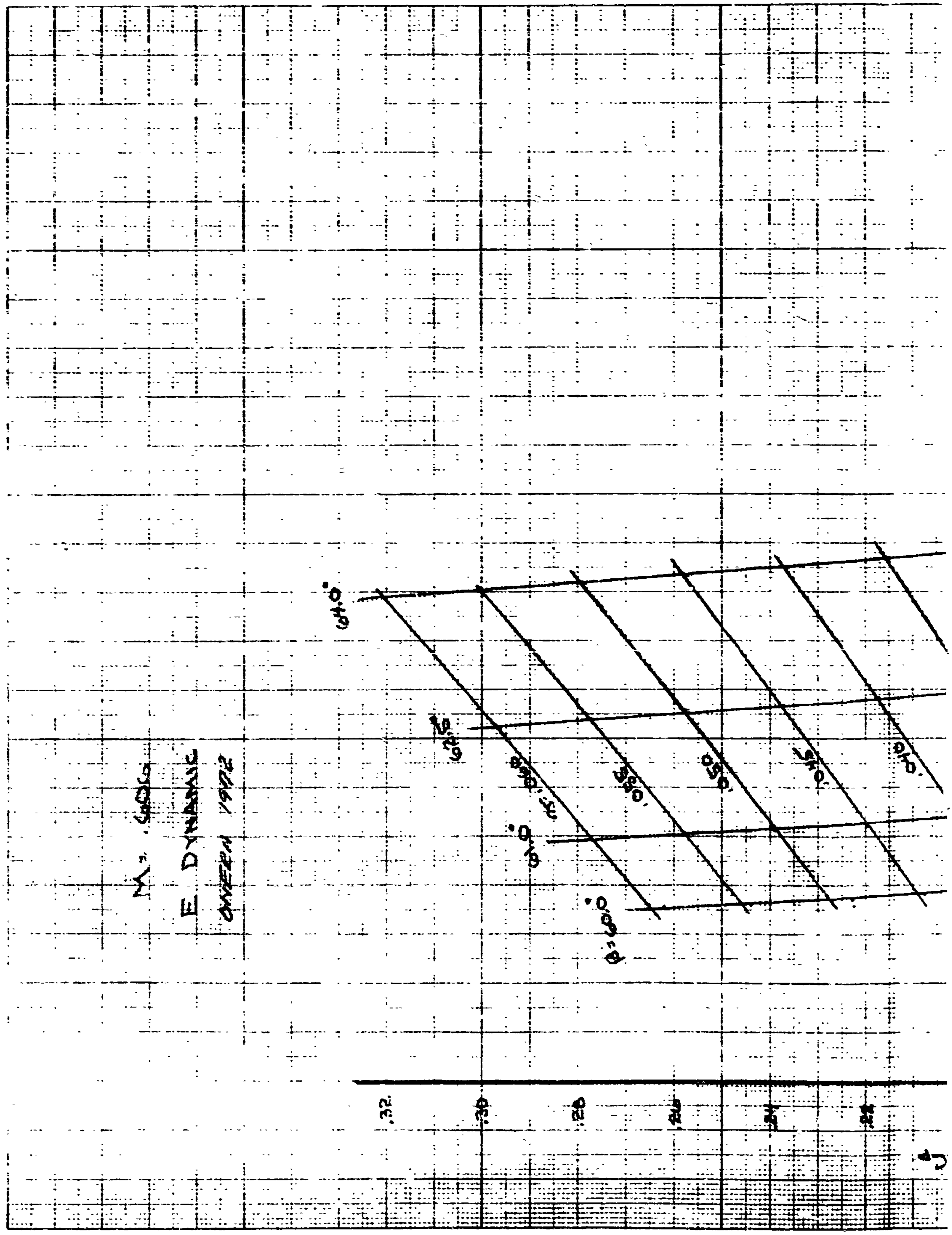
FOLDOUT FRAME 1

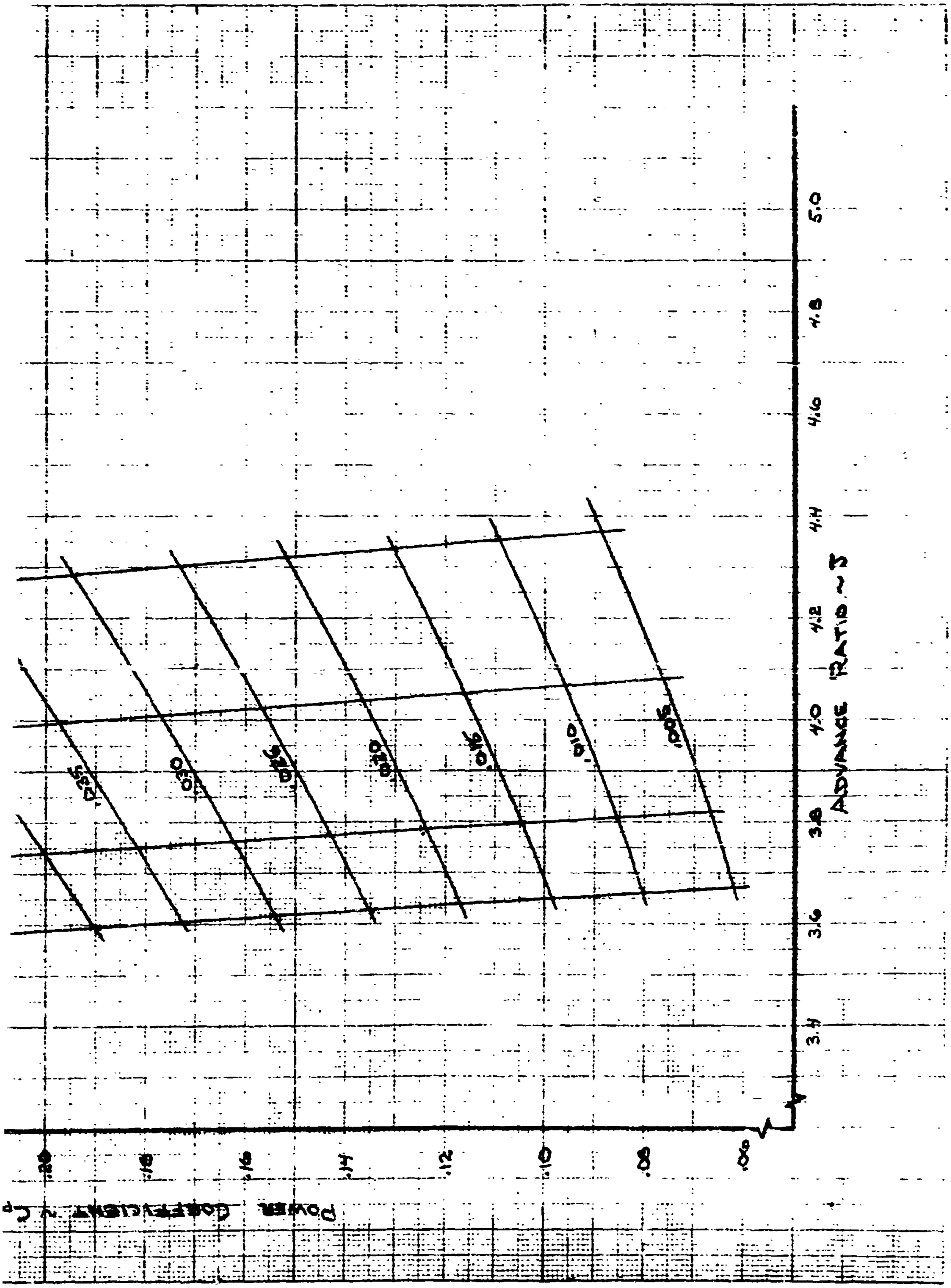
PAGE IS POOR.

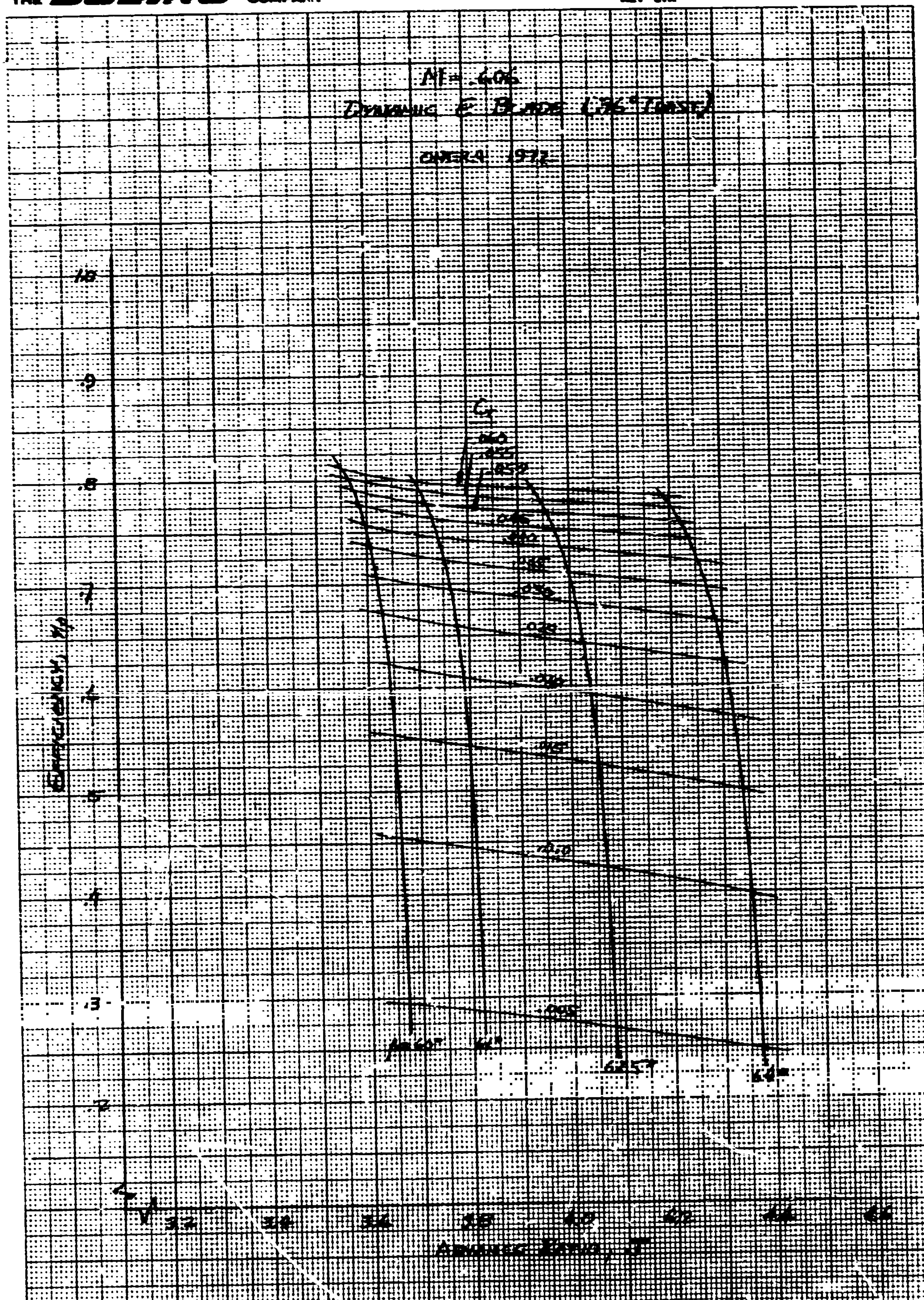


FOLDOUT FRAME 2


G
.9
.8
.7
.6
.5
.4
.3
.2
.005
.010
β=55°
57.5°
60°
61°
62.5°
2.8
3.0
3.2
3.4
3.6
3.8
4.0

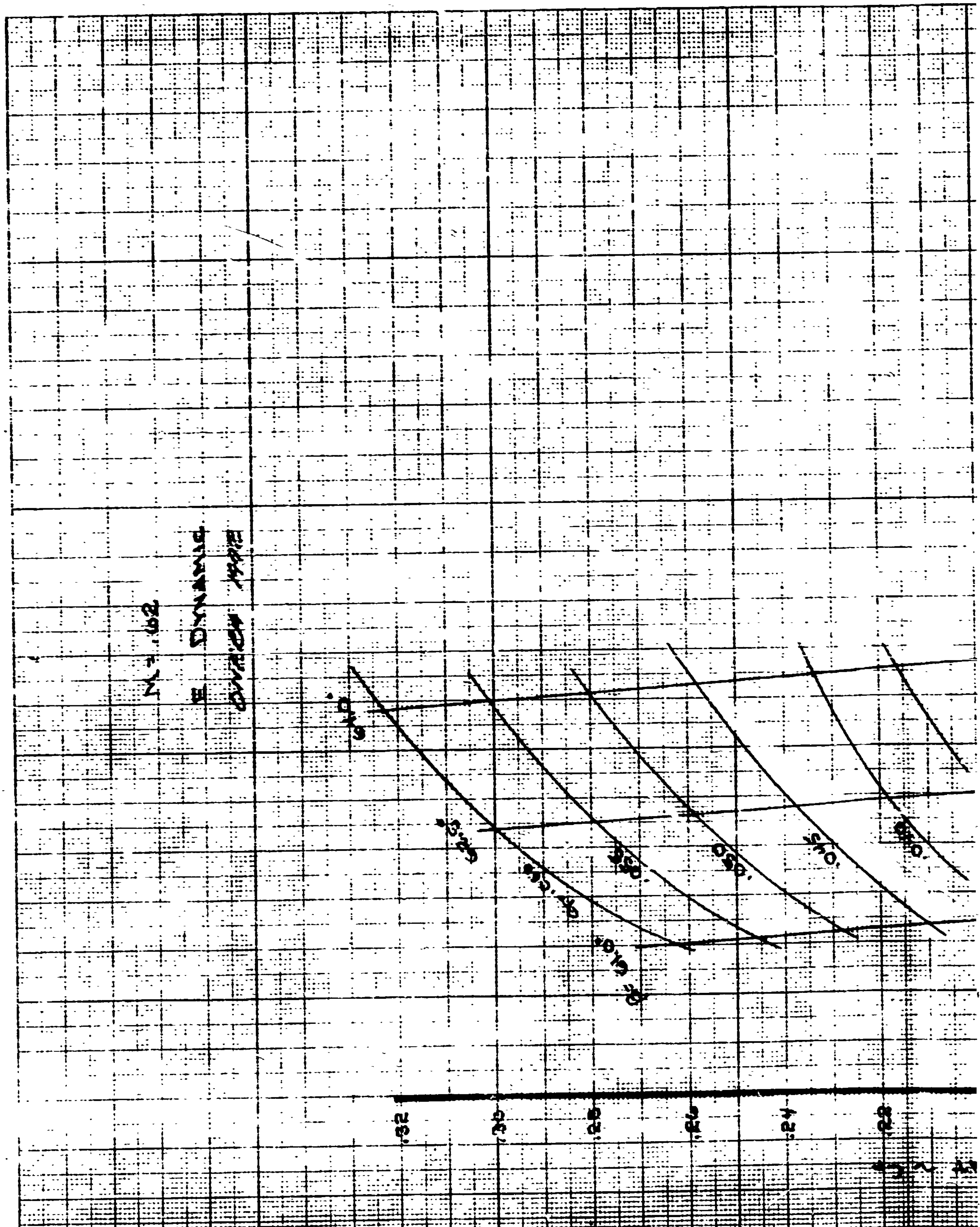

E DYNAMIC
.32
.30
.28


ADVANCE RATIO ~ J
POWER COEFFICIENT ~ C_P
3.4
3.6
3.8
4.0
4.2
4.4
4.6
4.8
5.0
.06
.08
.10
.12
.14
.16
.18
.20
.035
.030
.025
.020
.015
.010
.005

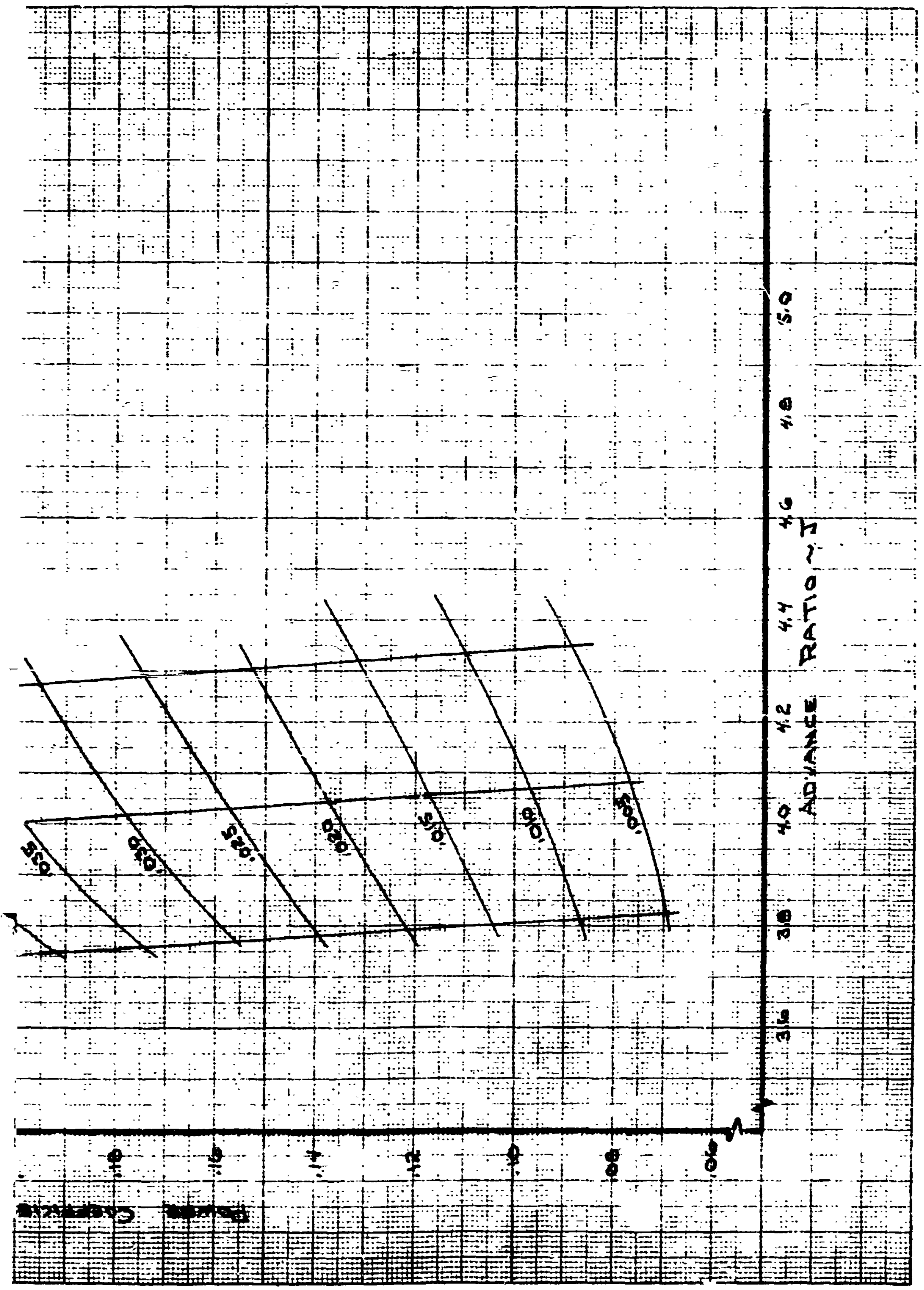


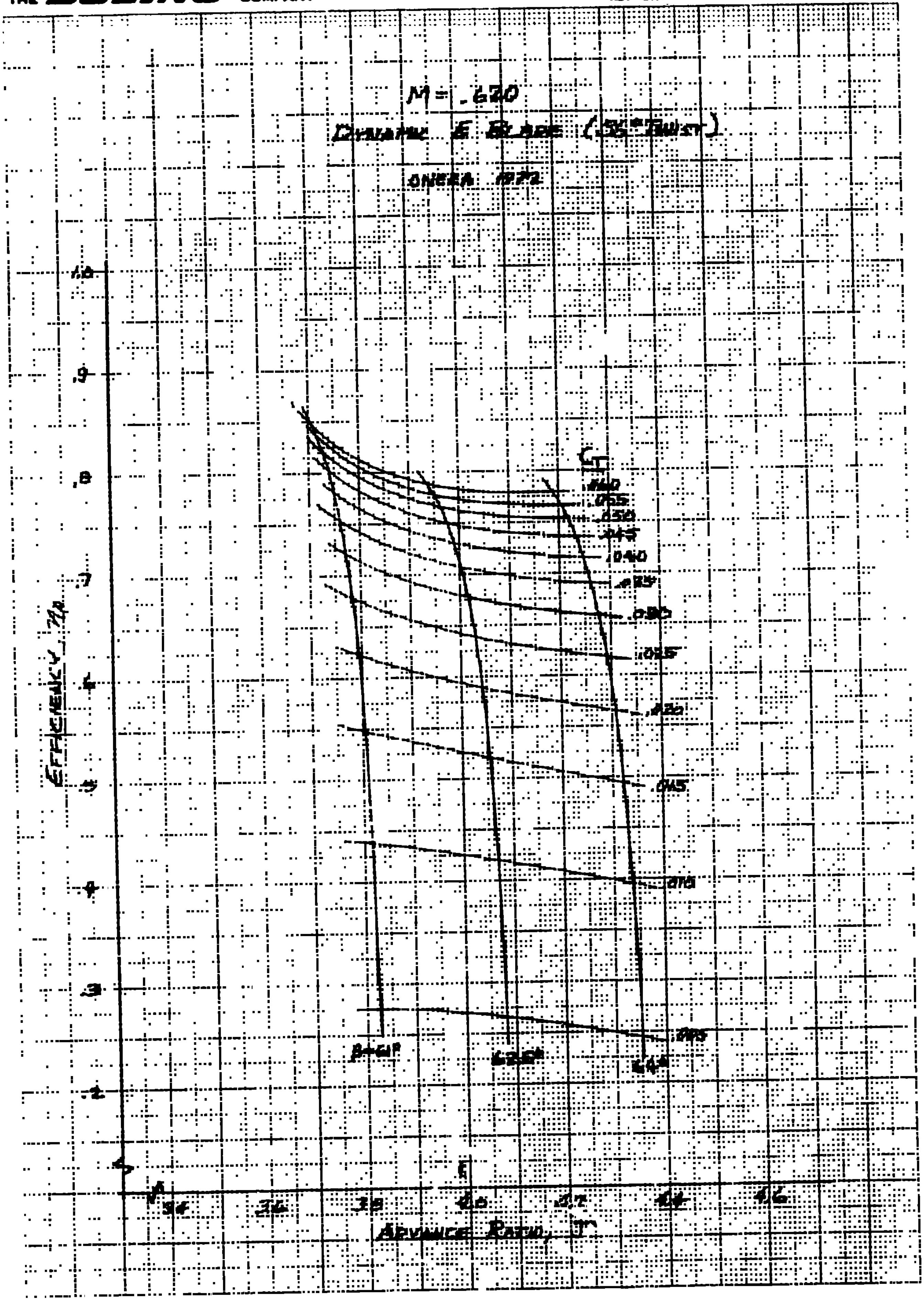
NO 340R-MP DIETZGEN GRAPH PAPER
MILLIMETER
EUGENE DIETZGEN CO.

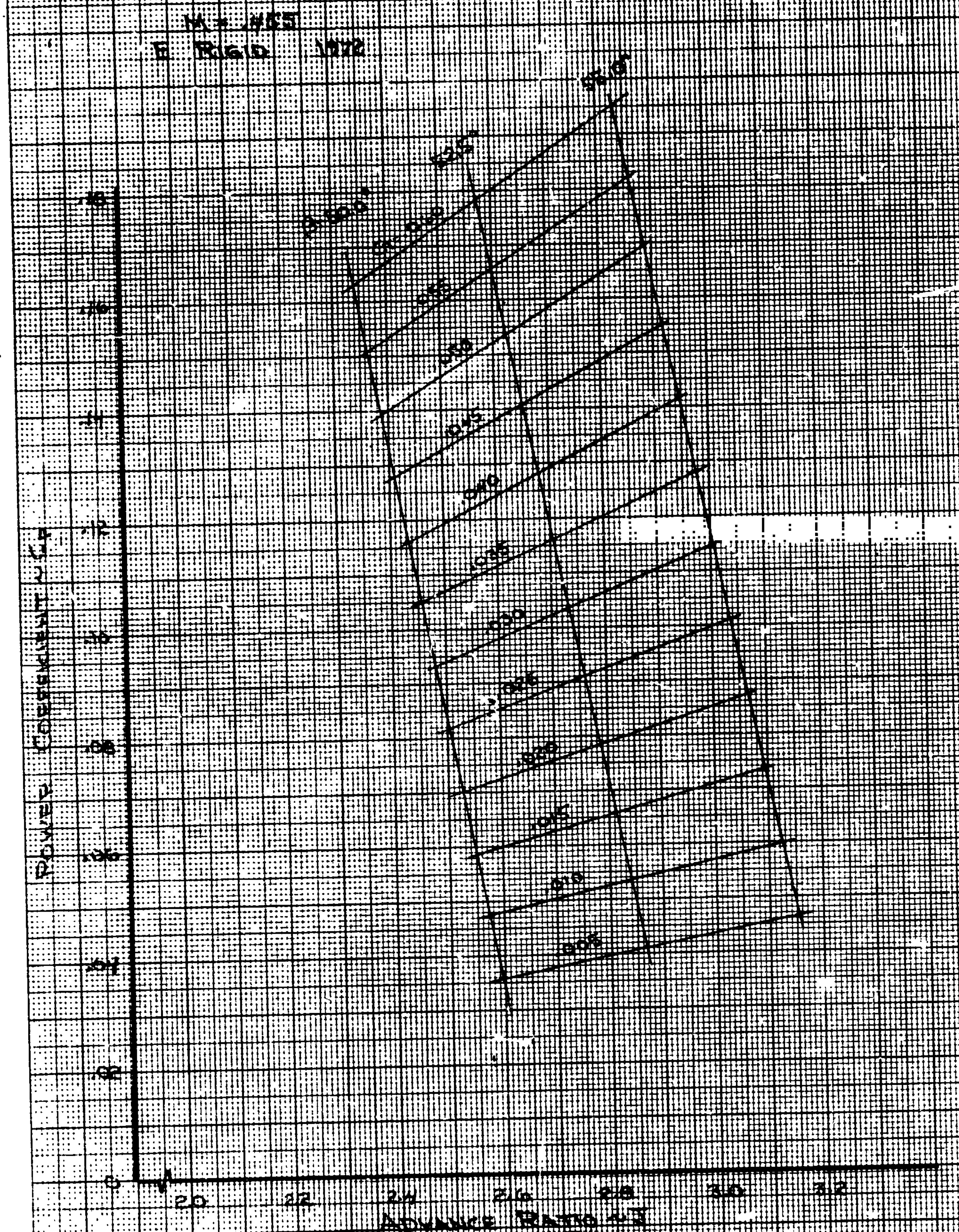
THE BOEING COMPANY



FOLDOUT FRAME-1

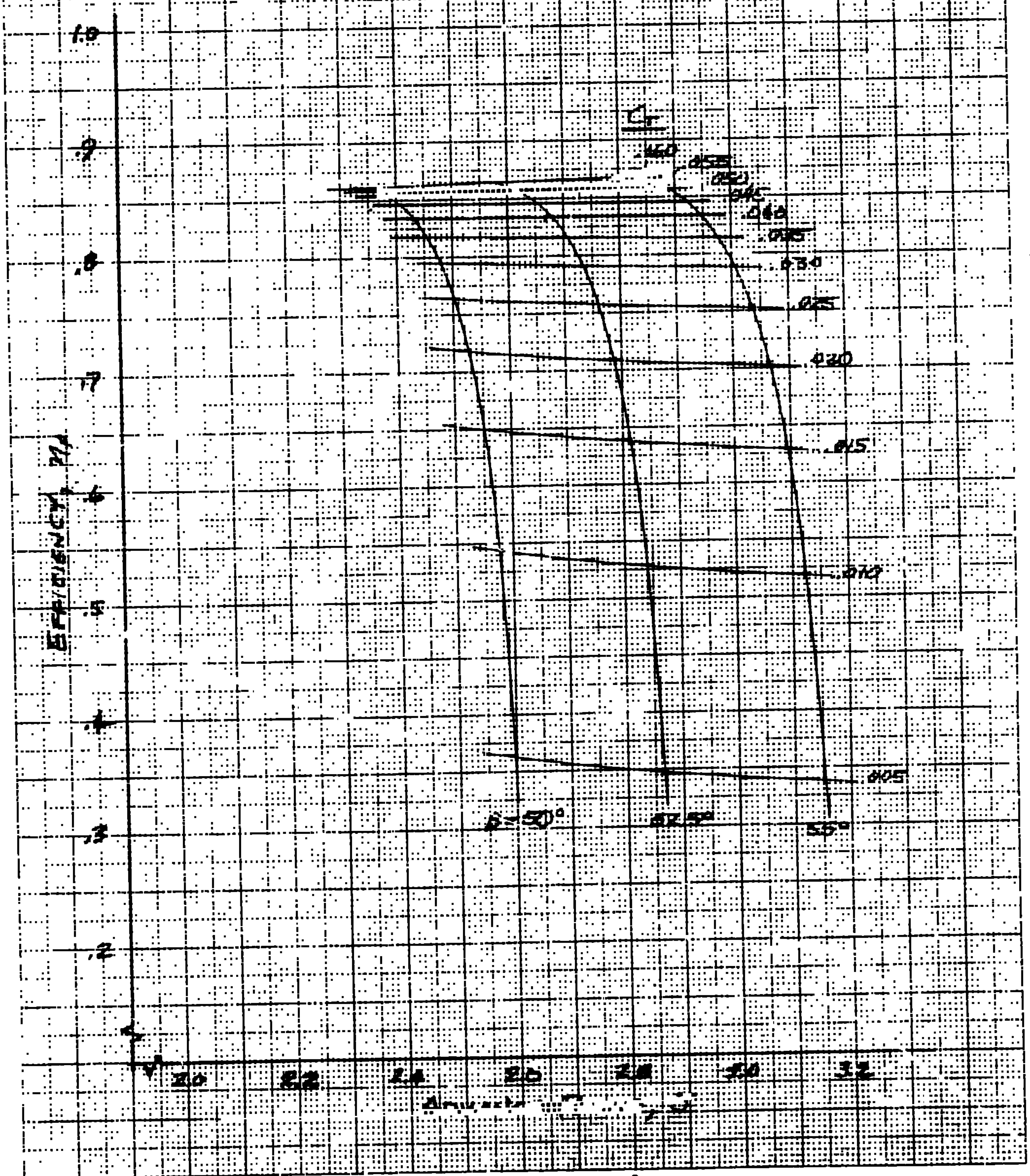

ADVANCE RATIO ~ J
3.6
3.8
4.0
4.2
4.4
4.6
4.8
5.0
.005
.010
.015
.020
.025
.030
.035
.06
.08
.10
.12
.14
.16
.18

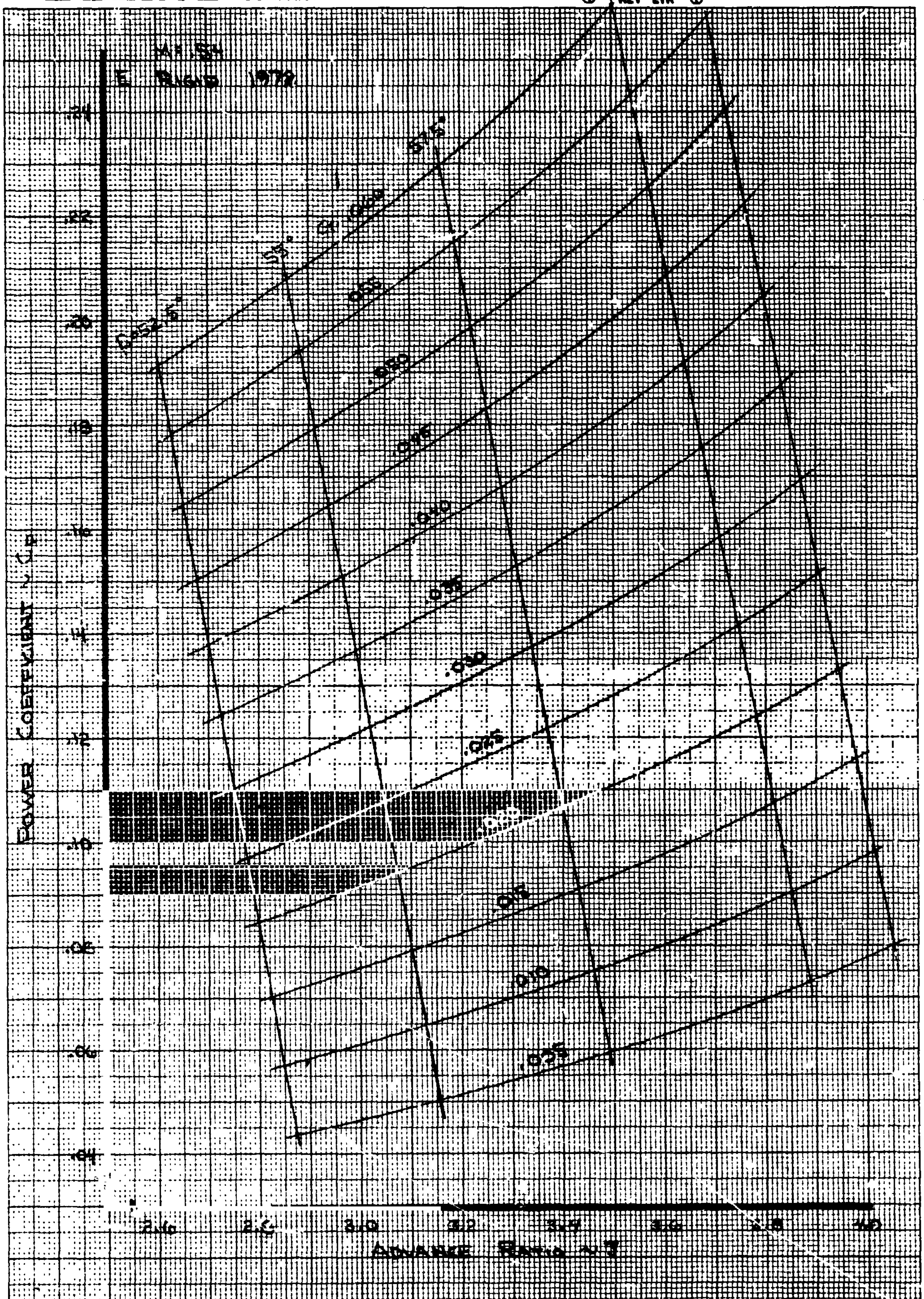

M = .620
DYNAMIC E BLADE (35° TWIST)
ONERA 1972
CT
.060
.055
.050
.045
.040
.035
.030
.025
.020
.015
.010
.005
1.0
.9
.8
.7
.6
.5
.4
.3
.2
3.4
3.6
3.8
4.0
4.2
4.4
4.6
EFFICIENCY, ηp
ADVANCE RATIO, J

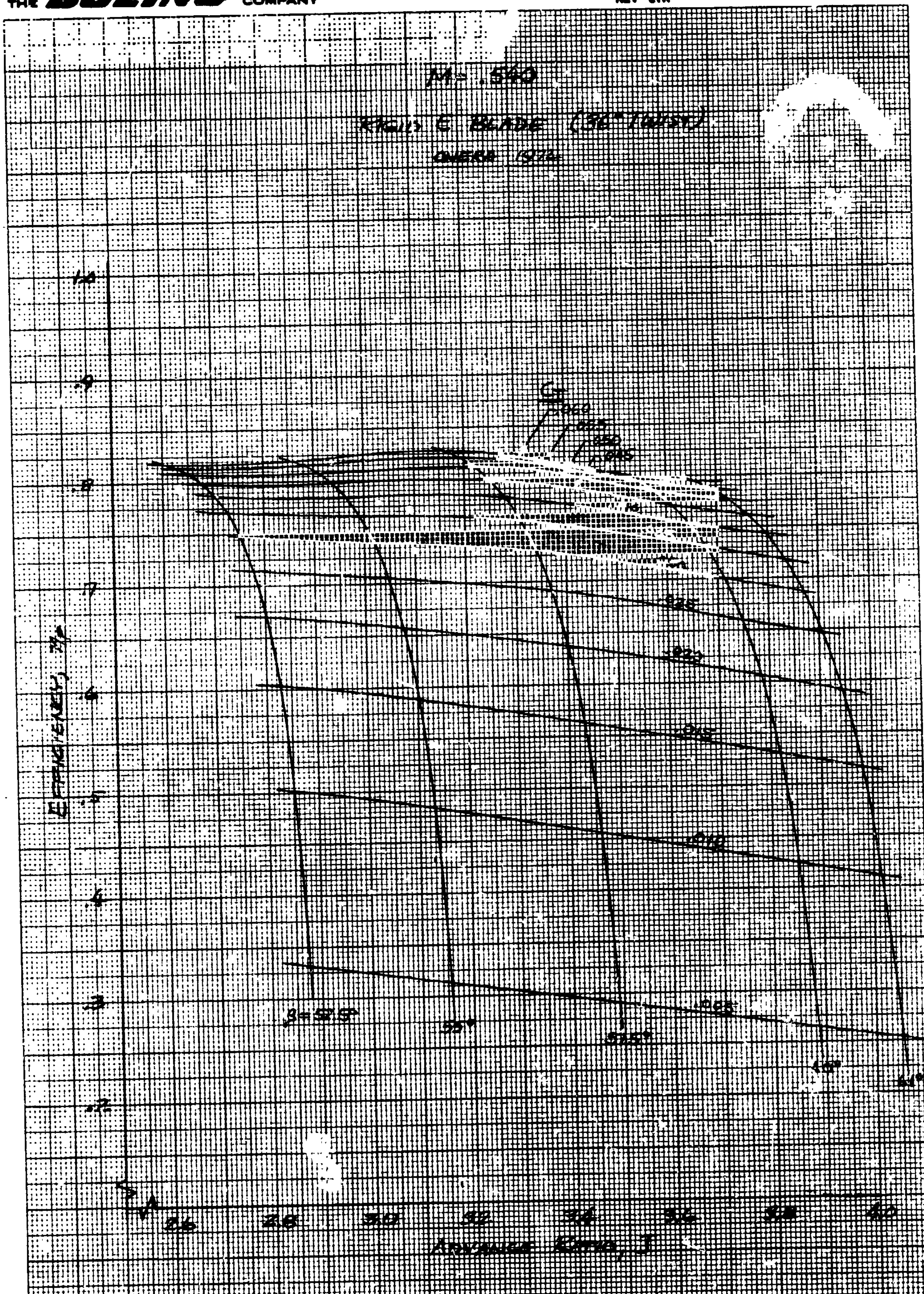


NO. 340R-MP DIETZGEN GRAPH PAPER MILLIMETER
EUGENE DIETZGEN CO. MADE IN U.S.A.

M = .455
Rigid E Blade (50° Twist)
ONERA 1972




.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
POWER COEFFICIENT ~ C_P
ADVANCE RATIO ~ J
θ=52.5°
55°
57.5°
60.0°
61.0°
.060
.055
.050
.045
.040
.035
.030
.025
.015
.010
.005


M = .540
RIGID E BLADE (36° TWIST)
ONERA 1974
EFFICIENCY, η_P
ADVANCE RATIO, J
2.6
2.8
3.0
3.2
3.4
3.6
3.8
4.0
β = 52.5°
55°
57.5°
60°
C_P
.010
.005

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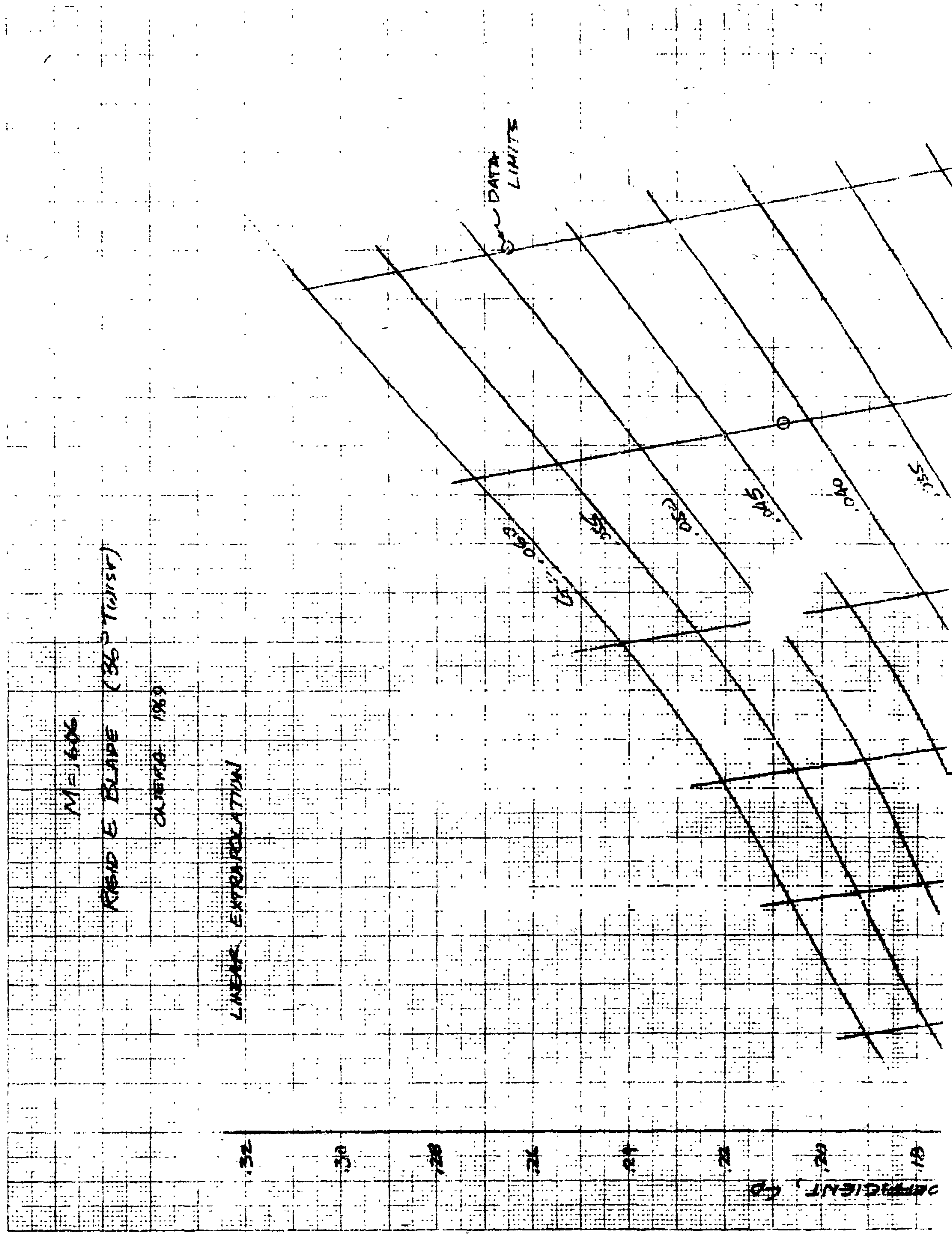
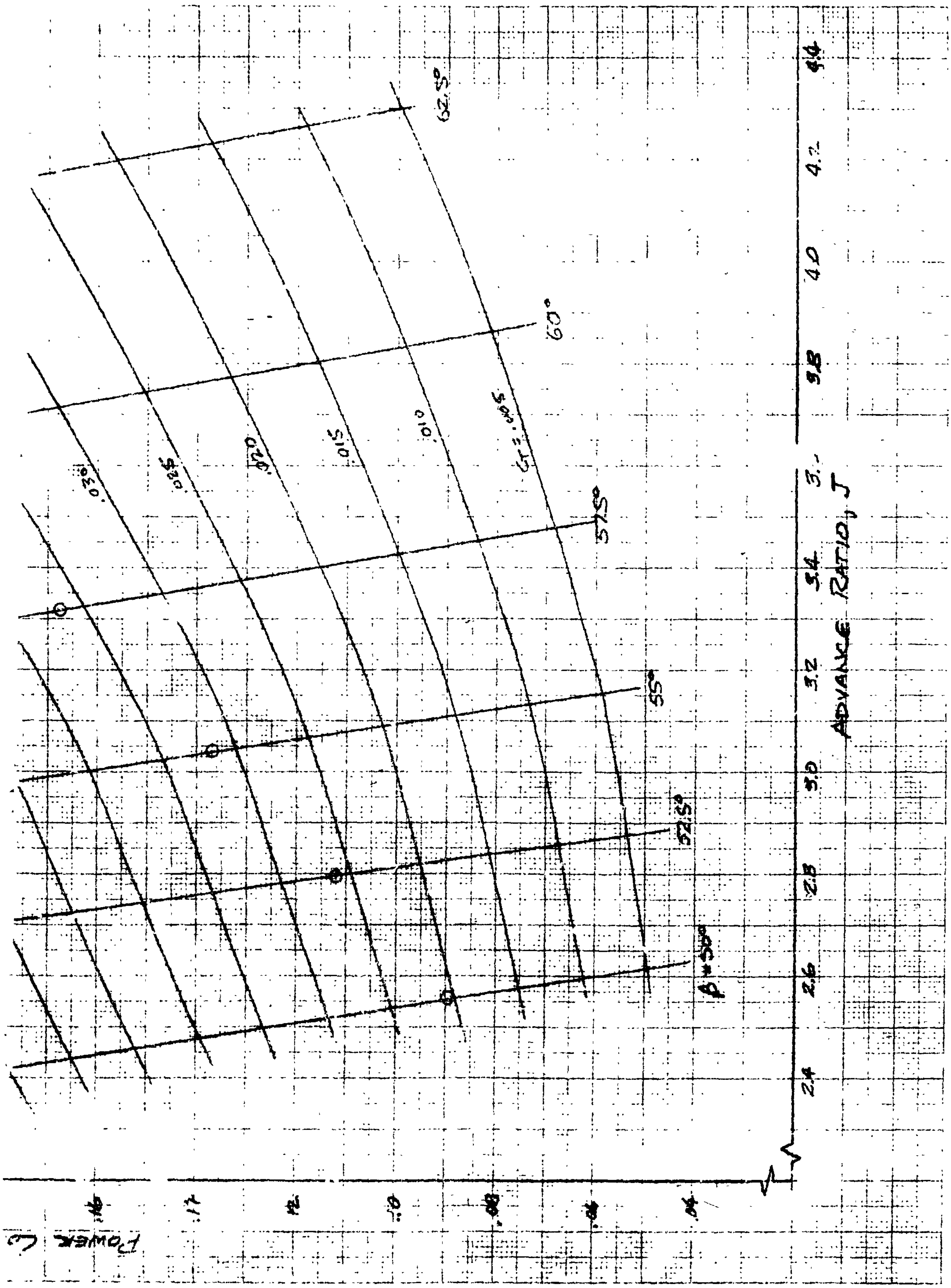


FOLDOUT FRAME 1

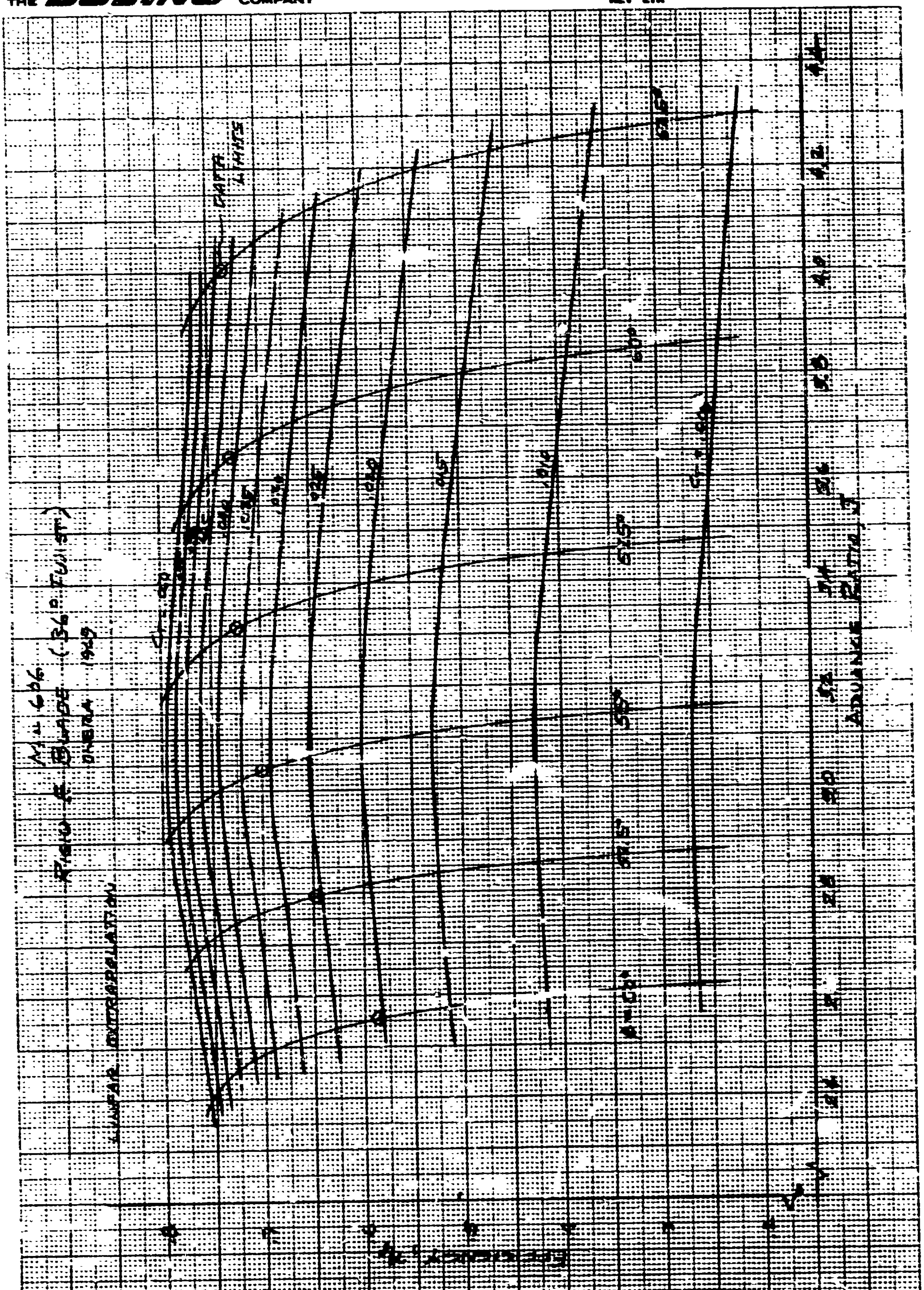


FOLDOUT FRAME 2

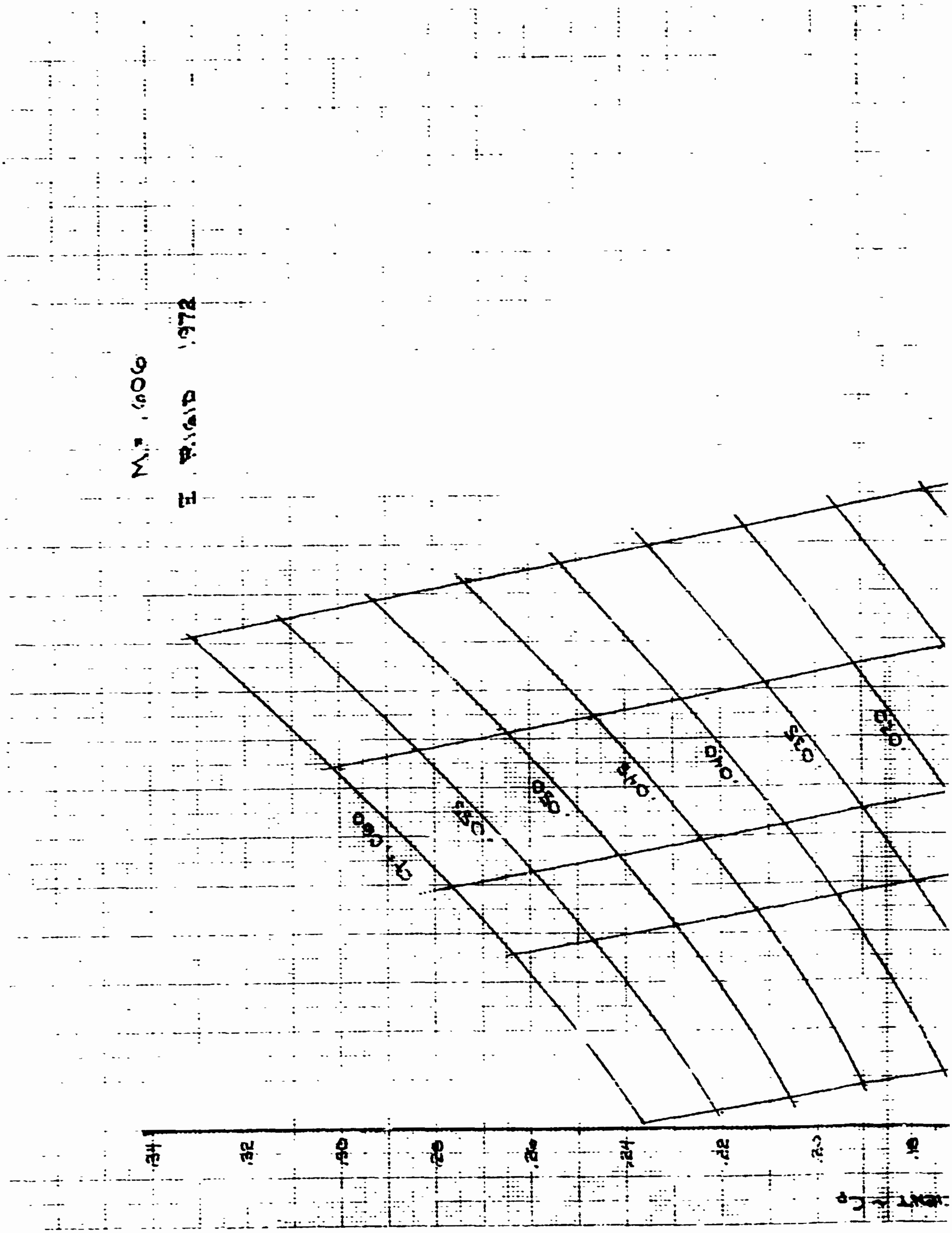
THE BOEING COMPANY

NUMBER D160-10021-1

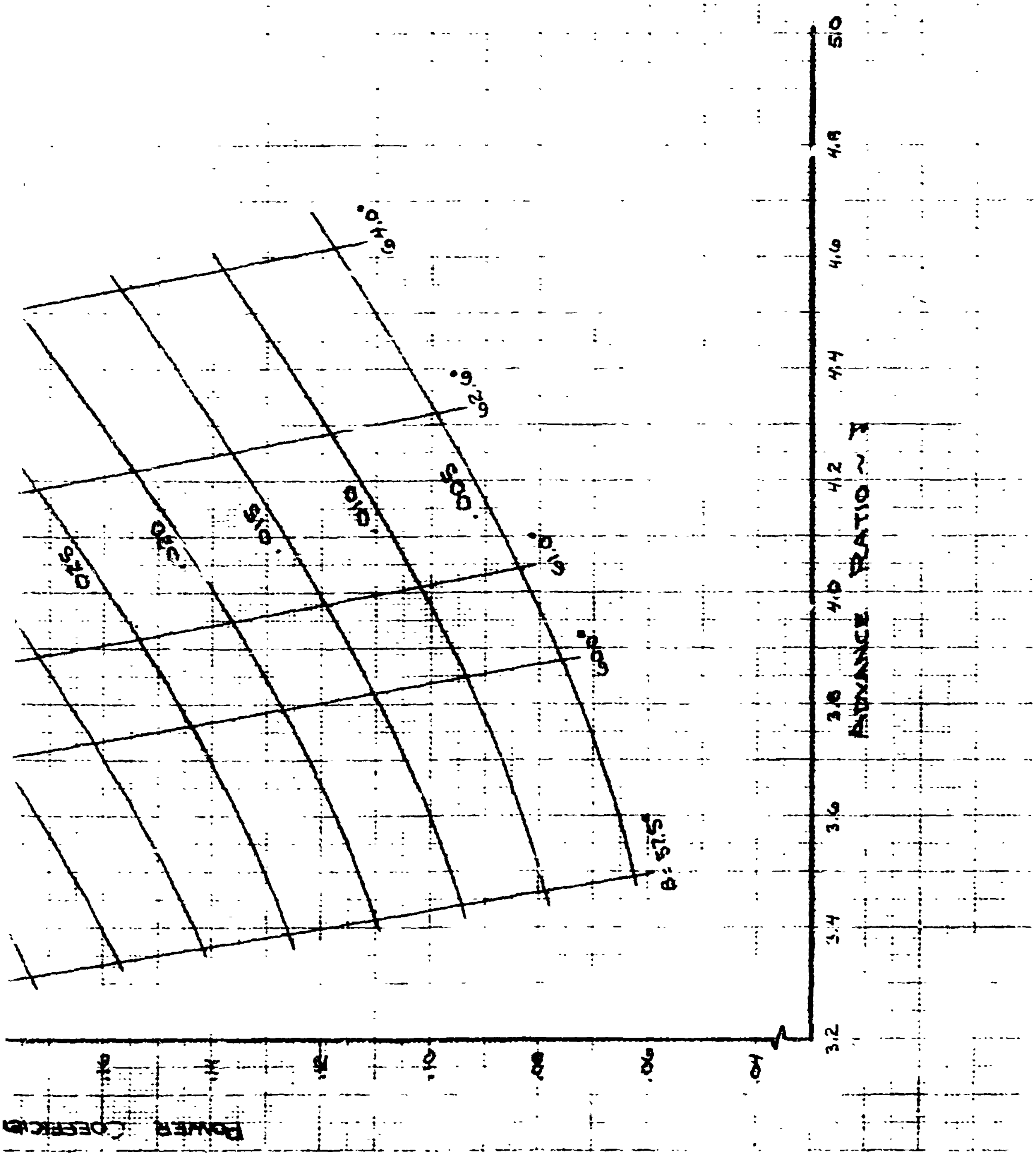
REV LTR



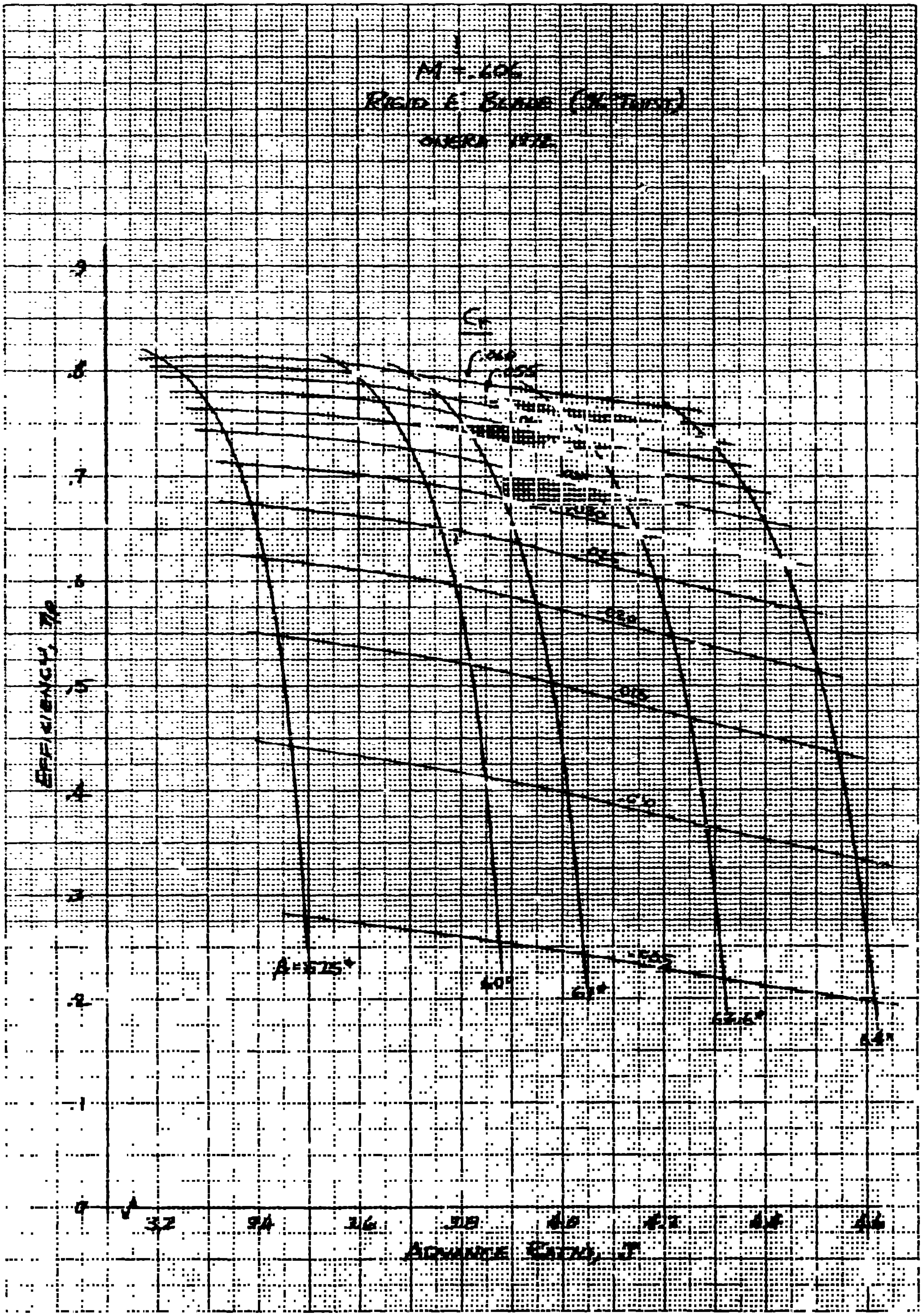
THE BOEING COMPANY



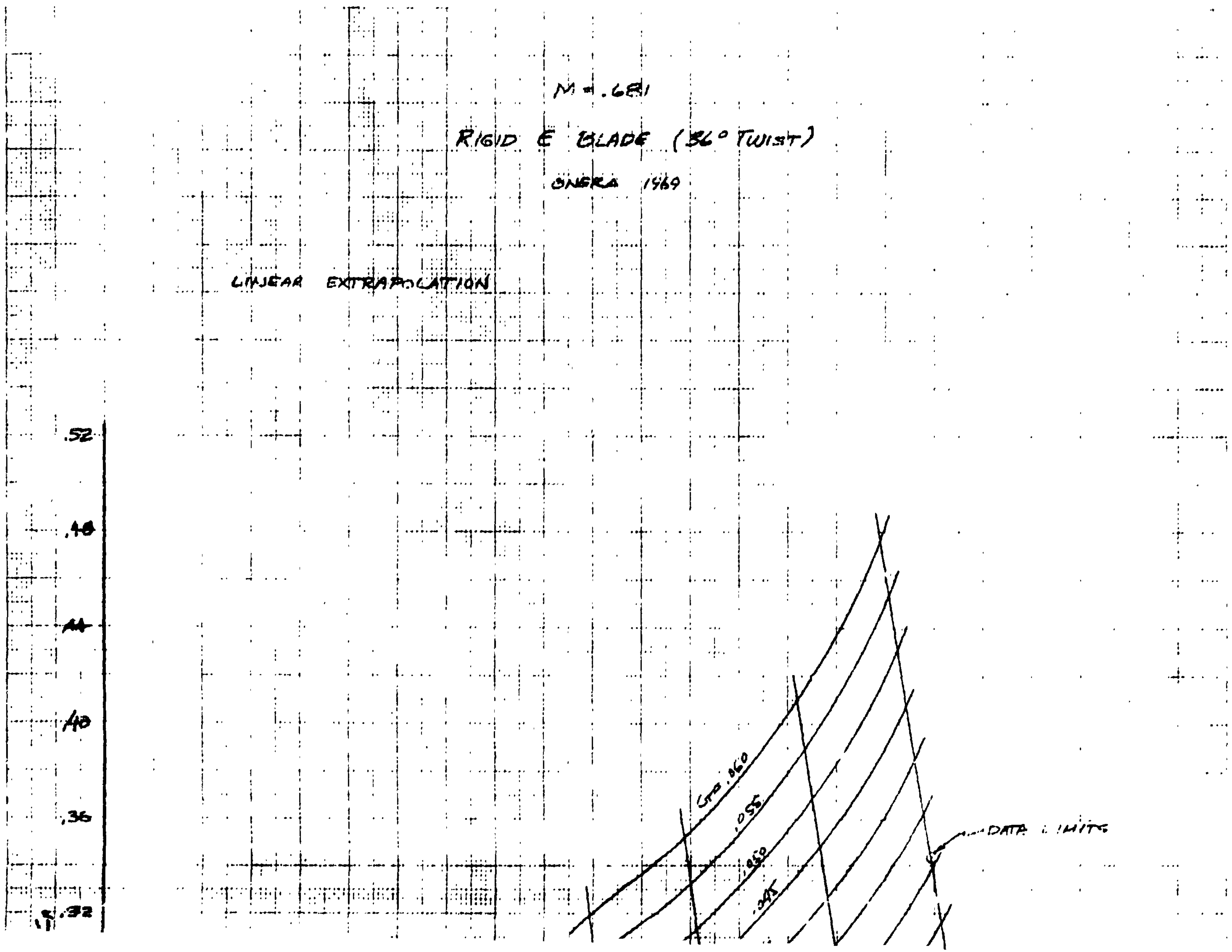
FC



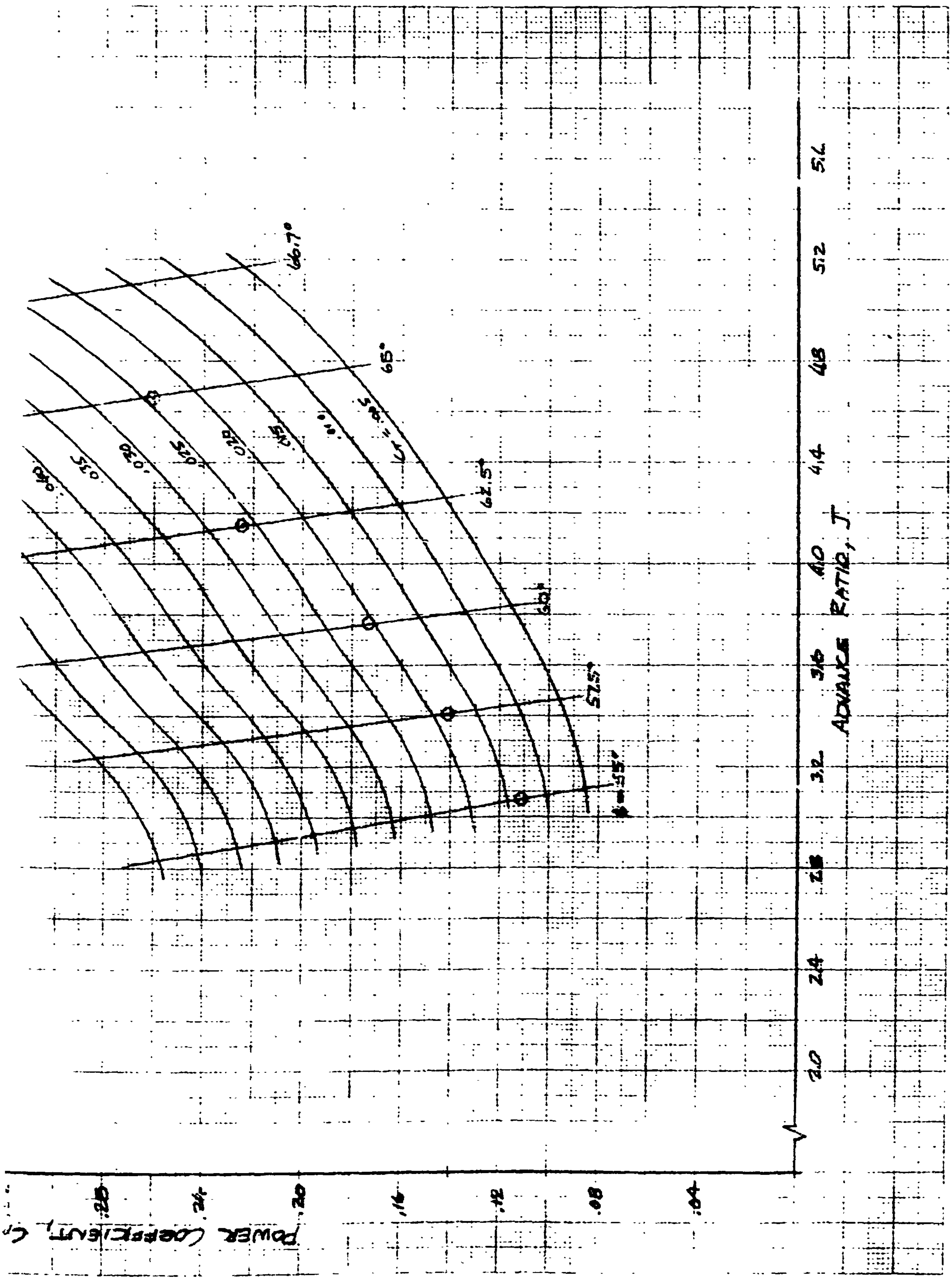
FOLDOUT FRAME 2

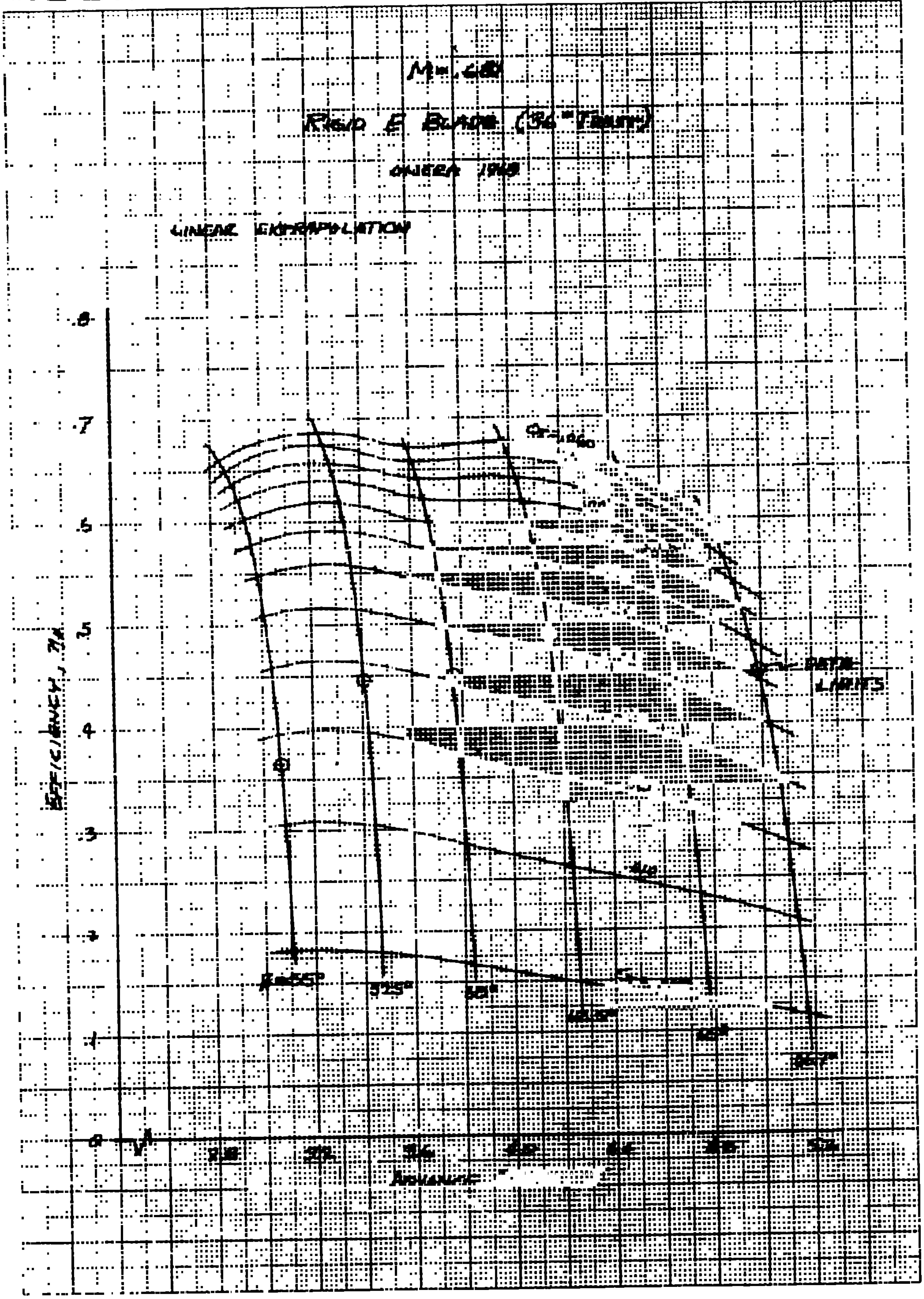


THE BOEING COMPANY

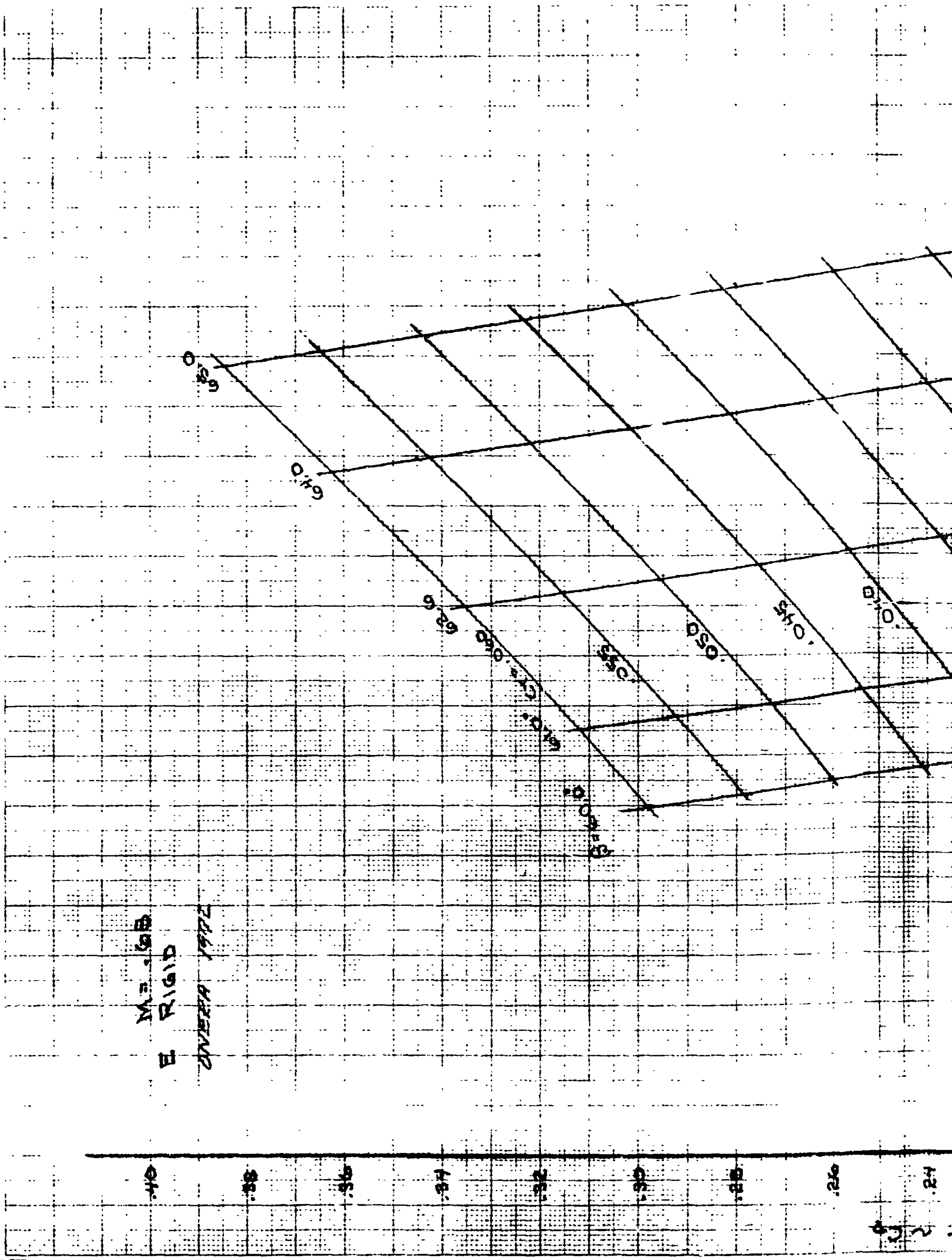


FOLDOUT FRAME 1


ADVANCE RATIO, J
POWER COEFFICIENT, C_P
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
.04
.08
.12
.16
.20
.24
.28
β = 55°
57.5°
60.0°
62.5°
65°
66.7°

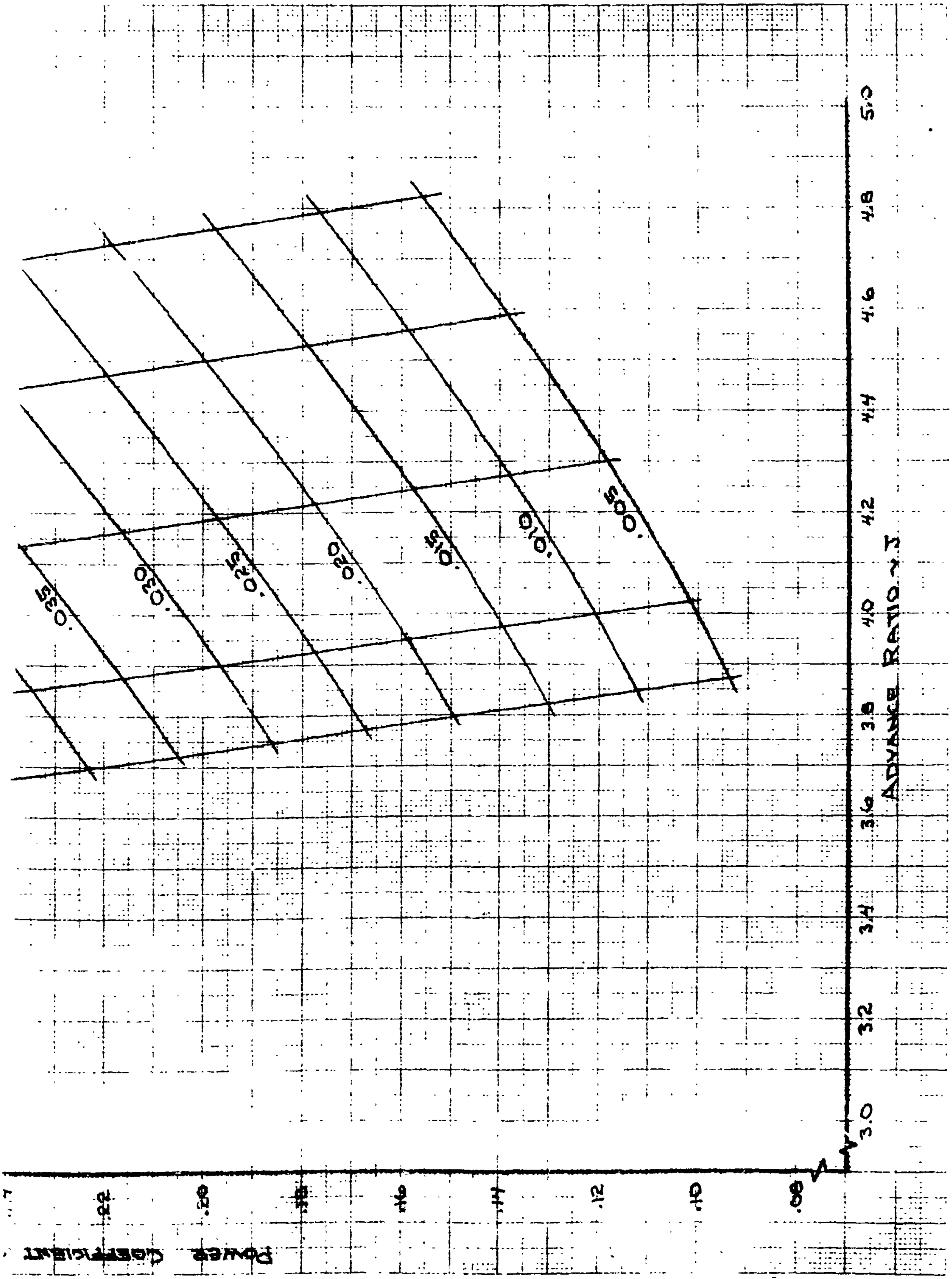


THE BOEING COMPANY



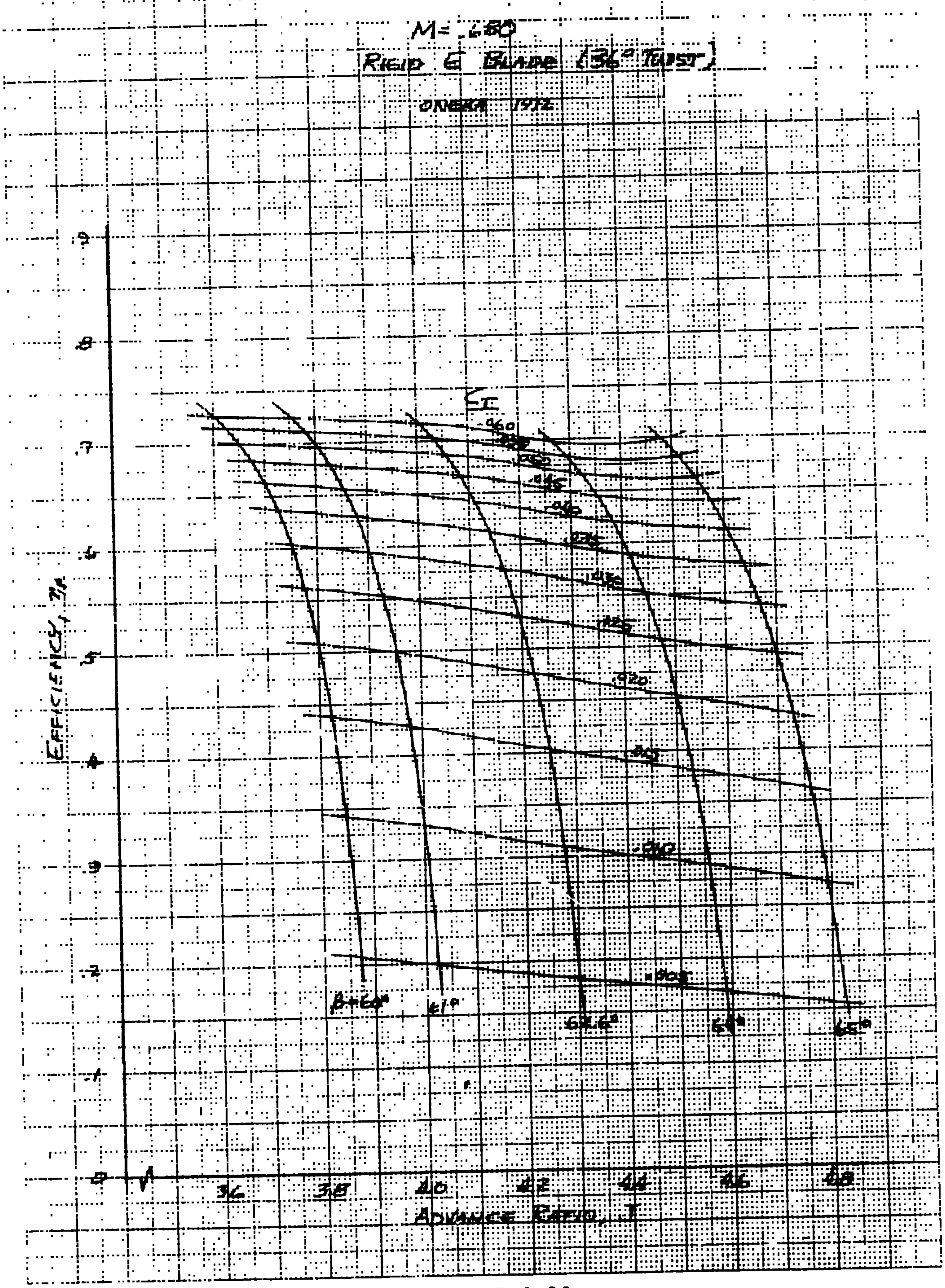
FOLDOUT FRAME 1

NUMBER D160-10021-1
REV LTR



SHEET

FOLDOUT FRAME 2

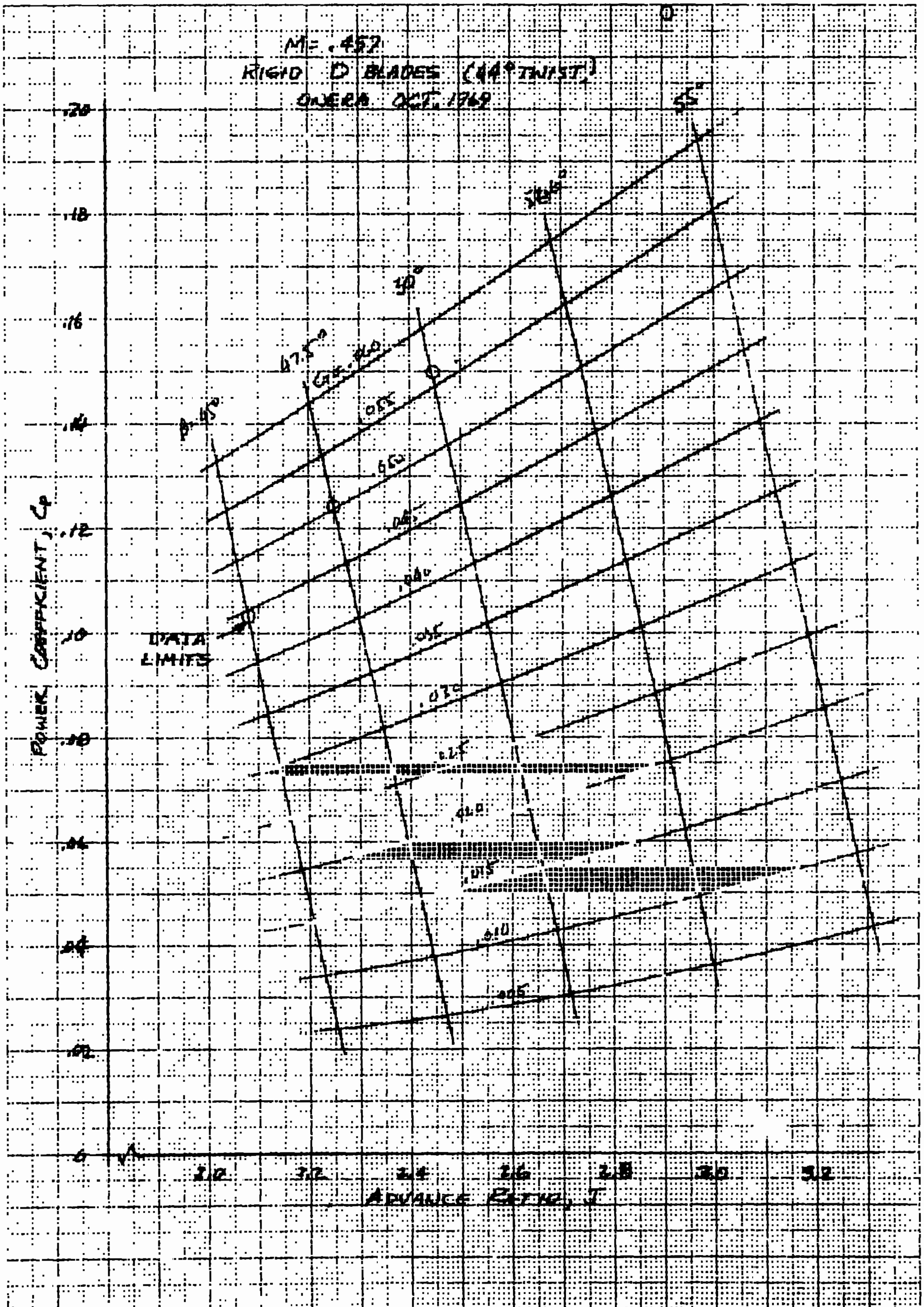

M = .680
RIGID E BLADE (36° TWIST)
ONERA 1972
C_T
EFFICIENCY, η_A
ADVANCE RATIO, J
β=60°
61°
62.6°
64°
65°
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
3.6
3.8
4.0
4.2
4.4
4.6
4.8

7.3 D BLADE CRUISE DATA

THE BOEING COMPANY

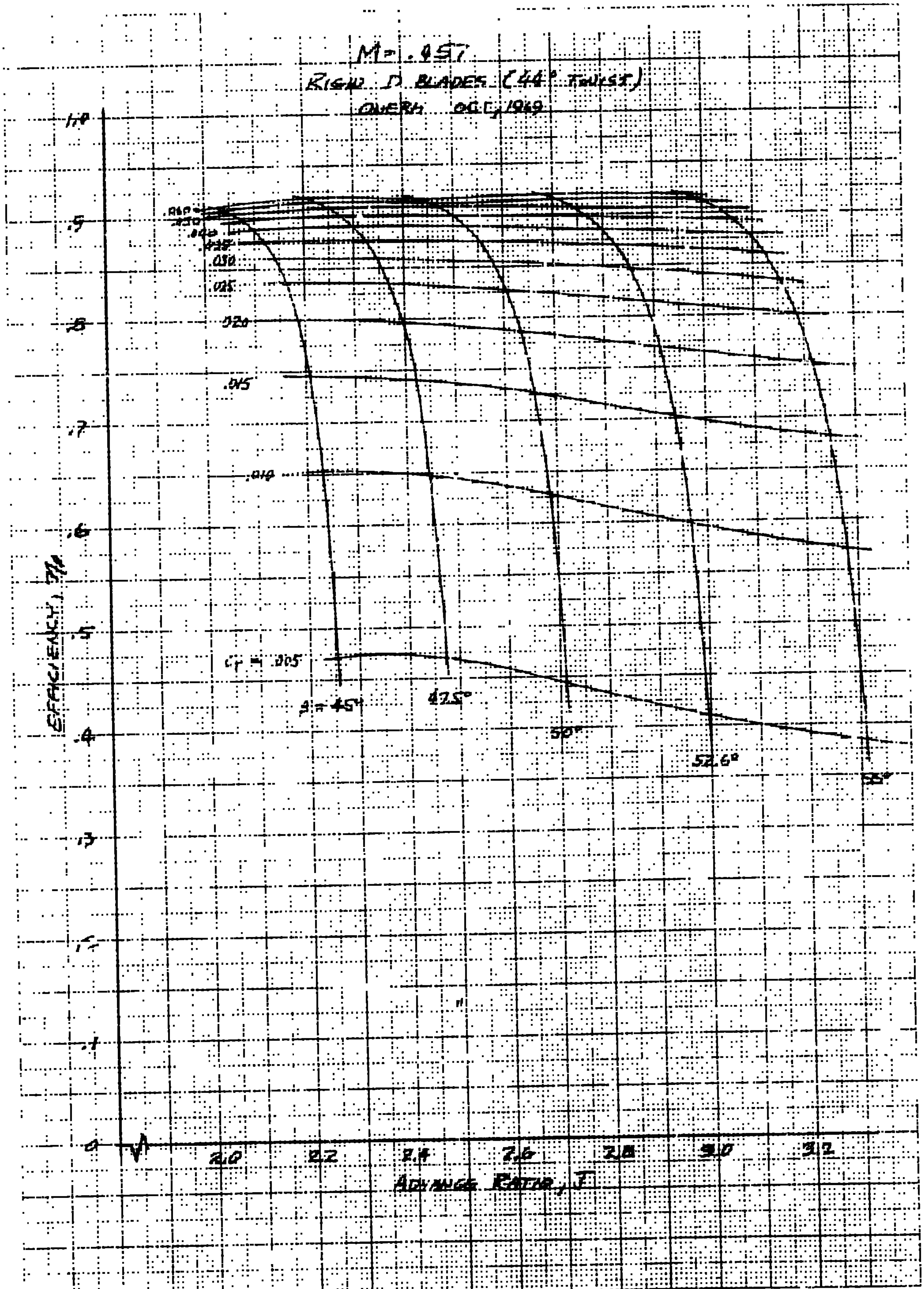
NUMBER D160-10021-1

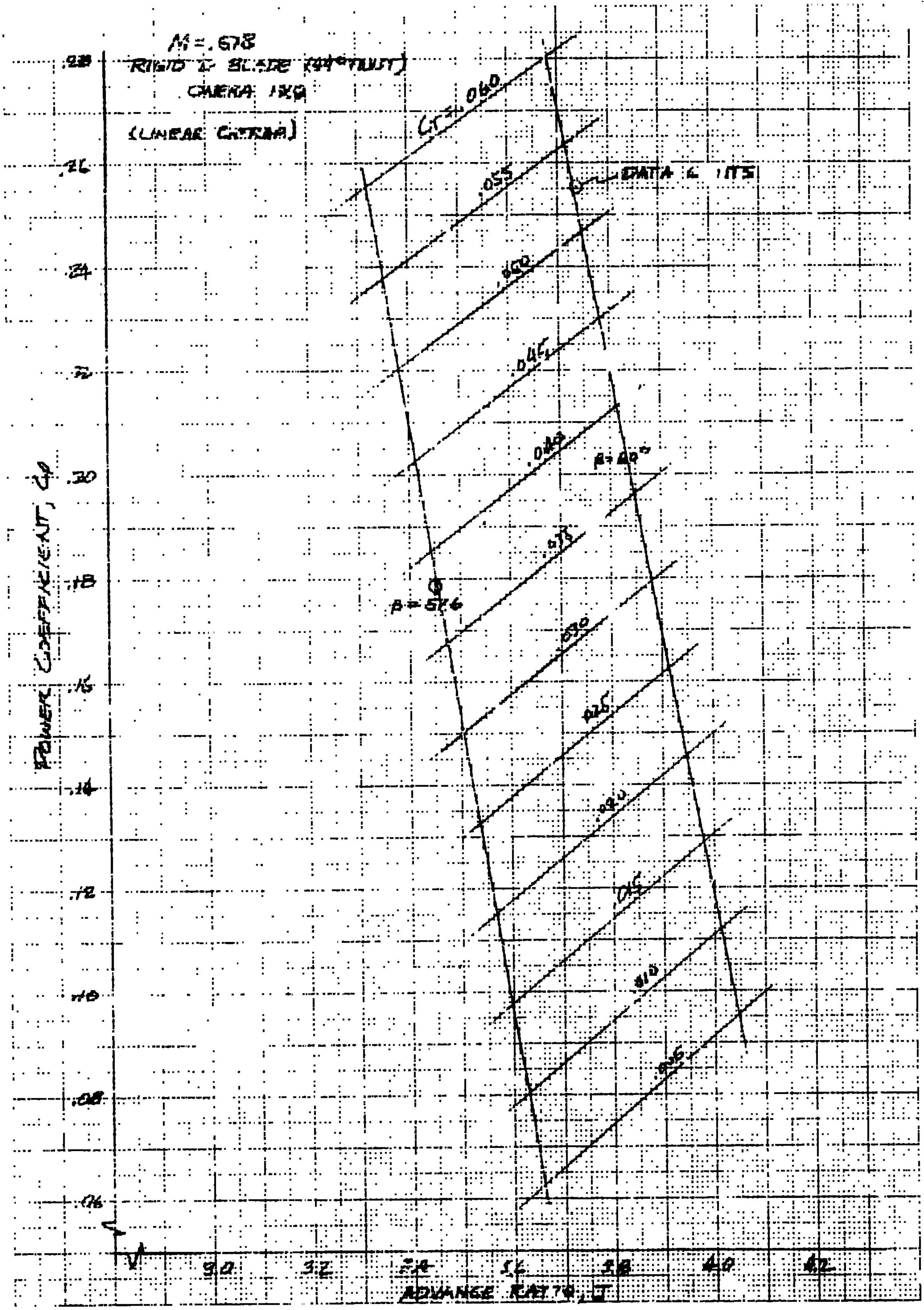
REV LTR

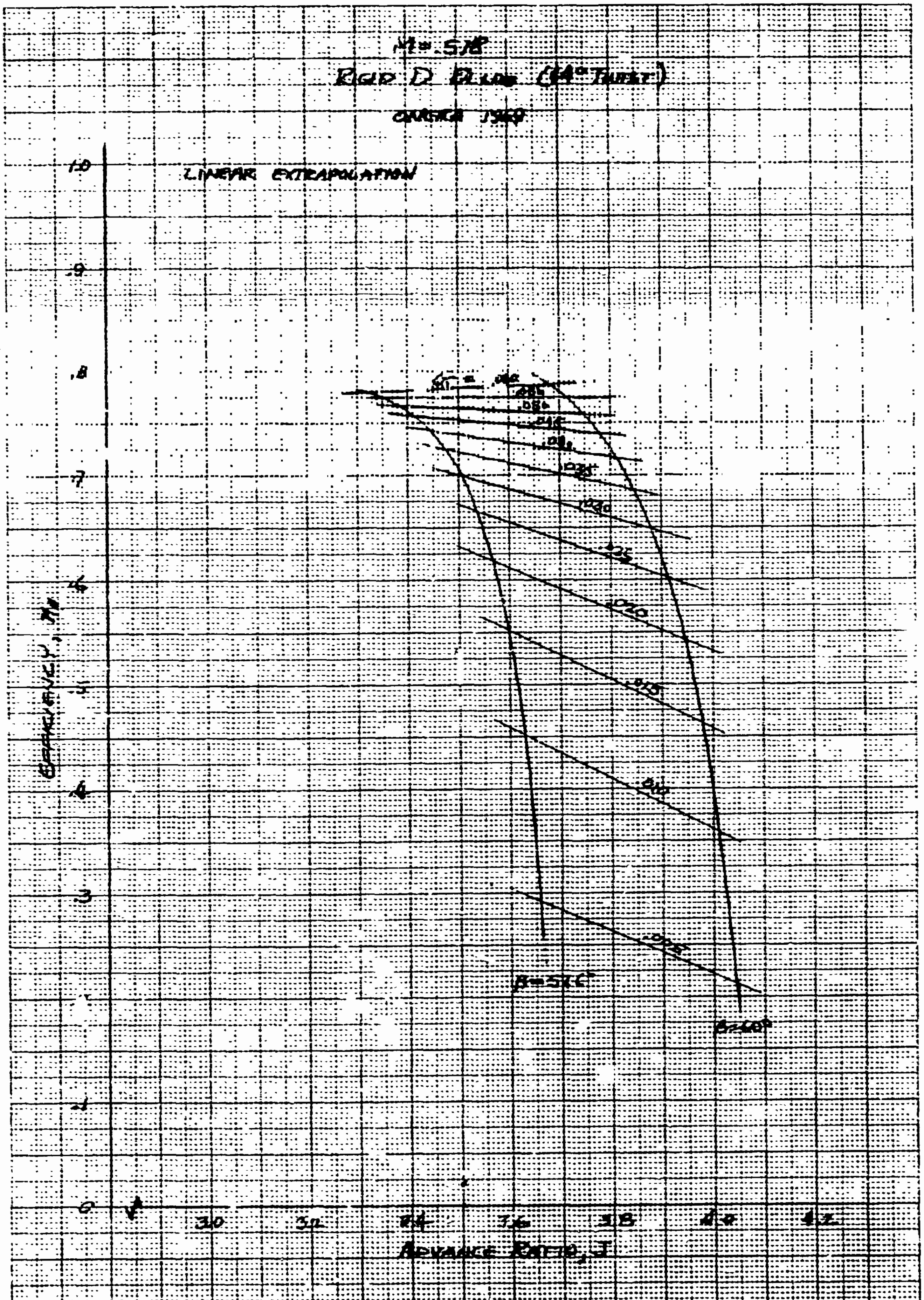


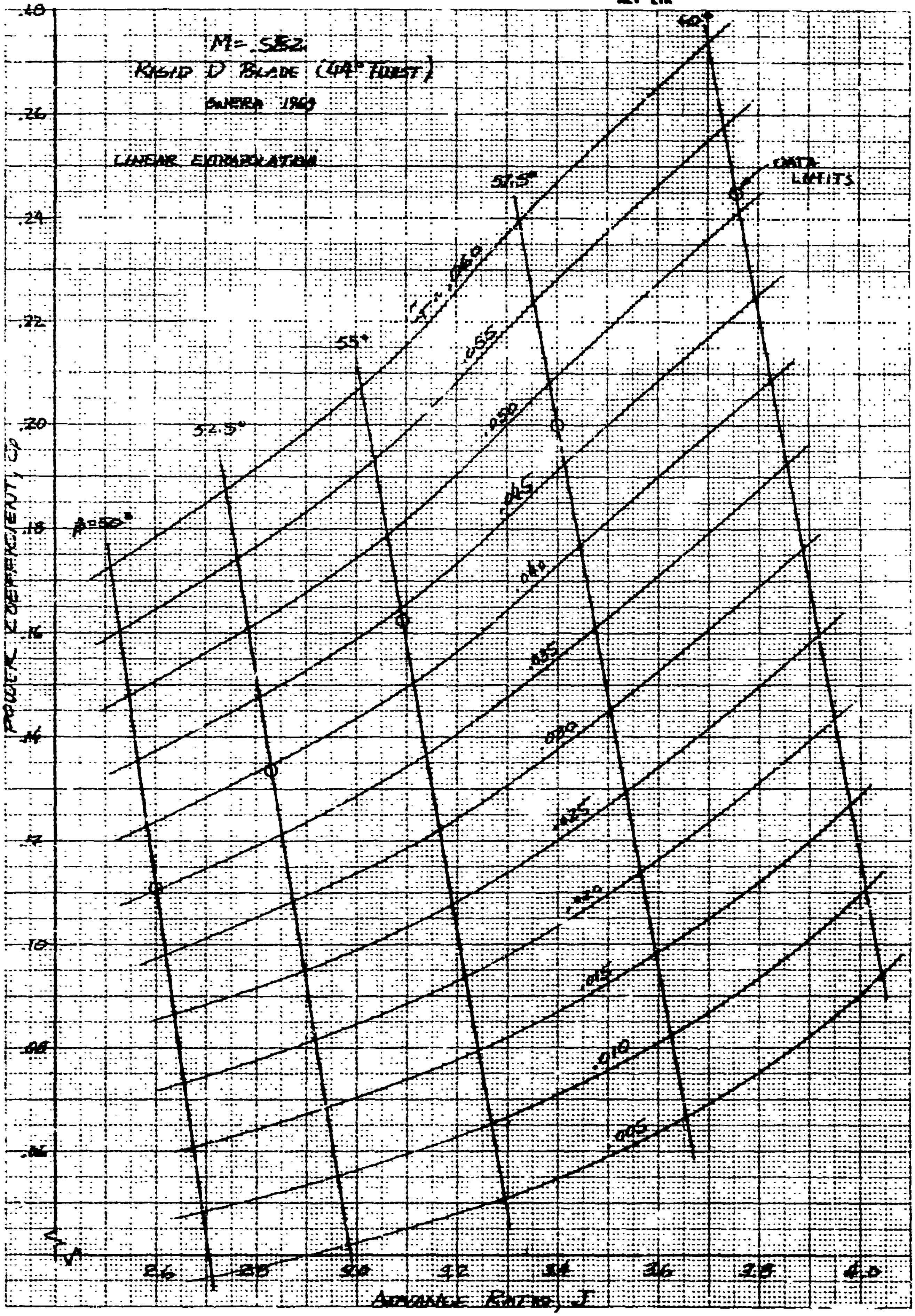
NO. 340R-MP DIETZGEN GRAPH PAPER MILLIMETER

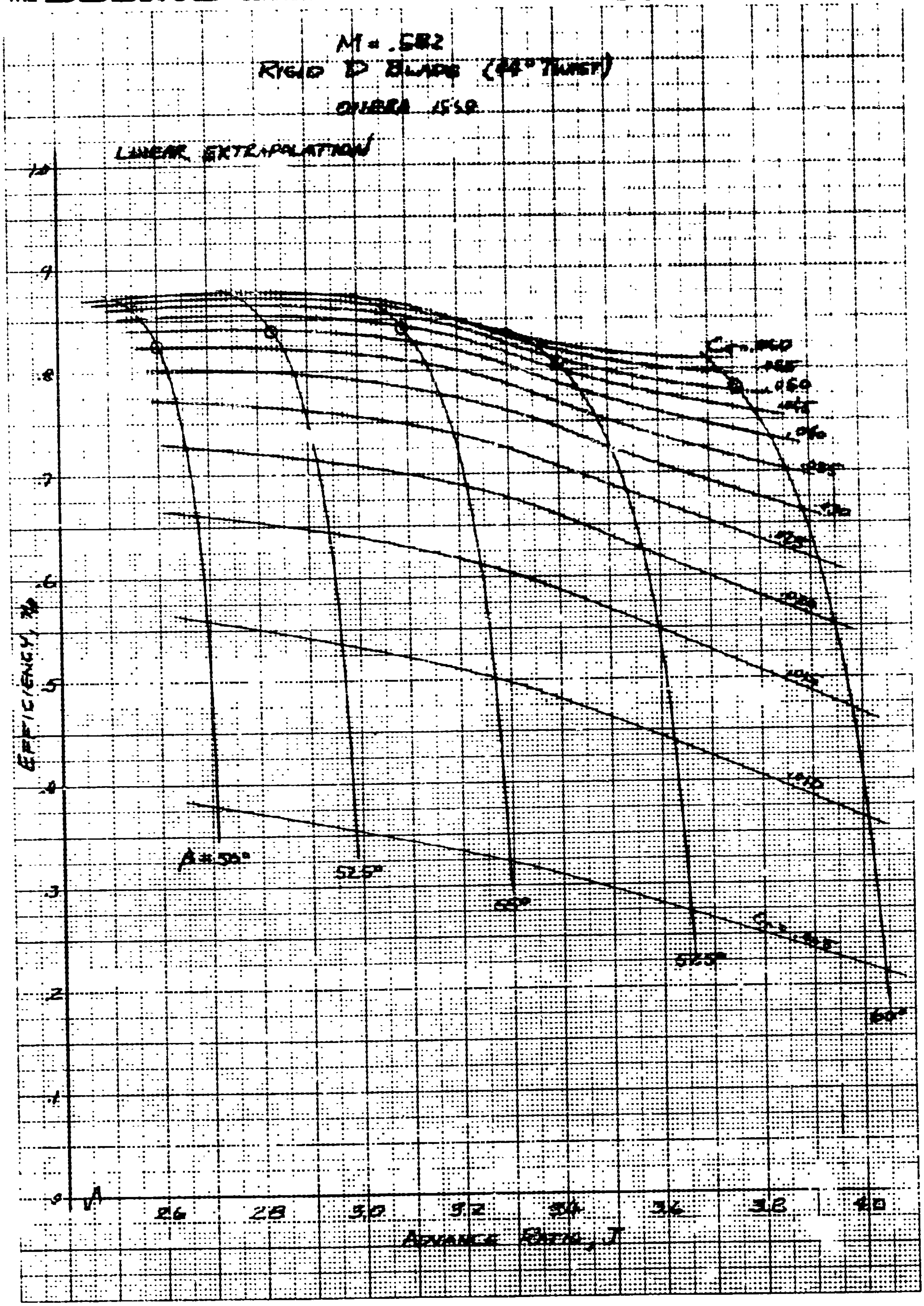
EUGENE DIETZGEN CO.


M = .457
RIGID D BLADES (44° TWIST)
OCT, 1949
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
EFFICIENCY, η
.060
.050
.040
.035
.030
.025
.020
.015
.010
C_P = .005
β = 45°
47.5°
50°
52.6°
55°
2.0
2.2
2.4
2.6
2.8
3.0
3.2
ADVANCE RATIO, J

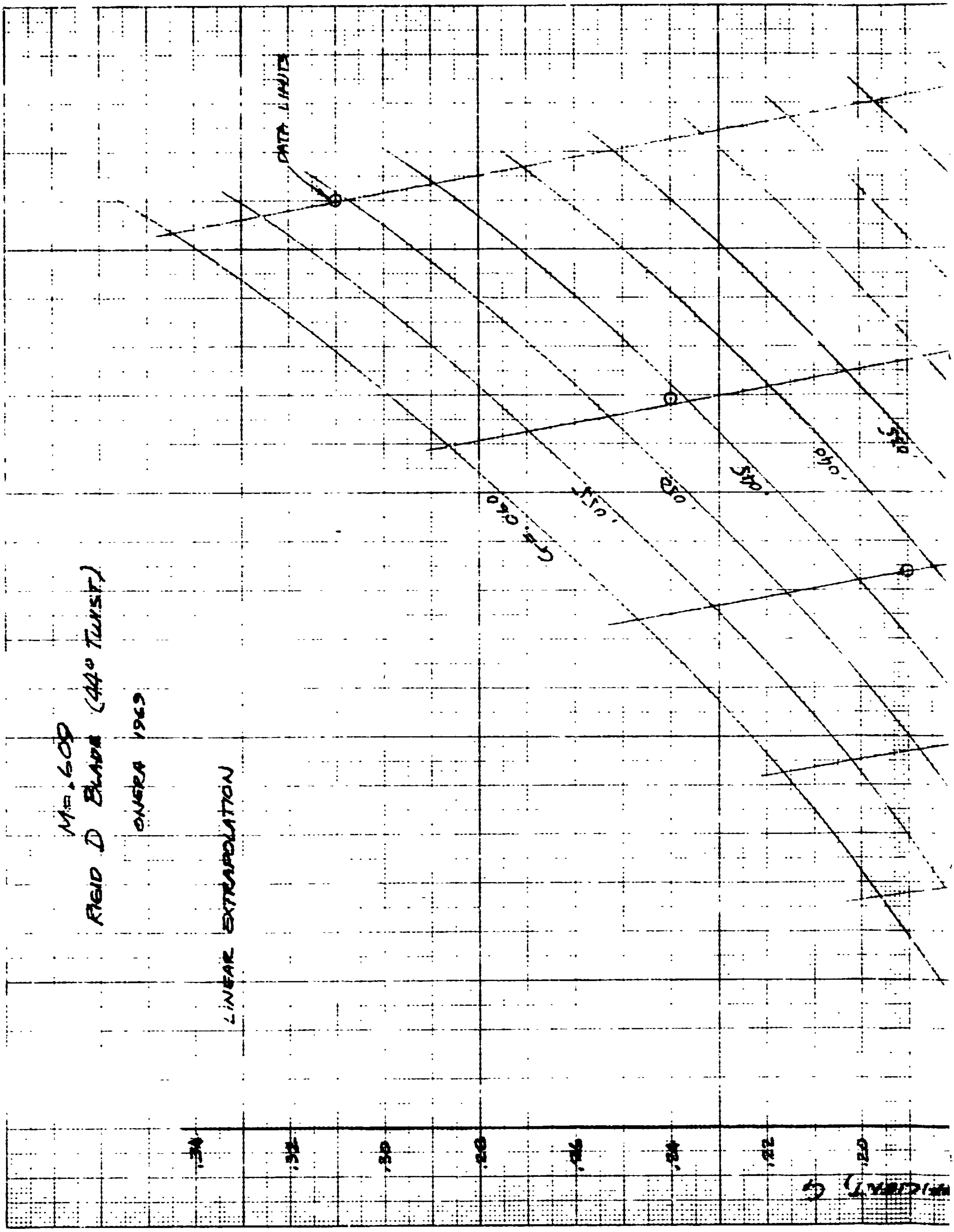

M = .678
POWER COEFFICIENT, C_P
ADVANCE RATIO, J
DATA LIMITS
β = 57.6
.28
.26
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06


LINEAR EXTRAPOLATION
1.0
.9
.8
.7
.6
.5
.4
.3
.1
0
3.0
3.2
3.4
3.6
3.8
4.0
4.2
ADVANCE RATIO, J


M = .582
RIGID D BLADE (44° TWIST)
LINEAR EXTRAPOLATION
DATA LIMITS
β=50°
52.5°
55°
57.5°
60°
.060
.055
.050
.045
.040
.035
.030
.025
.020
.015
.010
.005
POWER COEFFICIENT, C_P
ADVANCE RATIO, J
.28
.26
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
2.6
2.8
3.0
3.2
3.4
3.6
3.8
4.0


M = .582
Rigid D Blade (24° Twist)
LINEAR EXTRAPOLATION
EFFICIENCY, η
ADVANCE RATIO, J
β = 50°
52.5°
55°
57.5°
60°
Cp = .160

THE BOEING COMPANY



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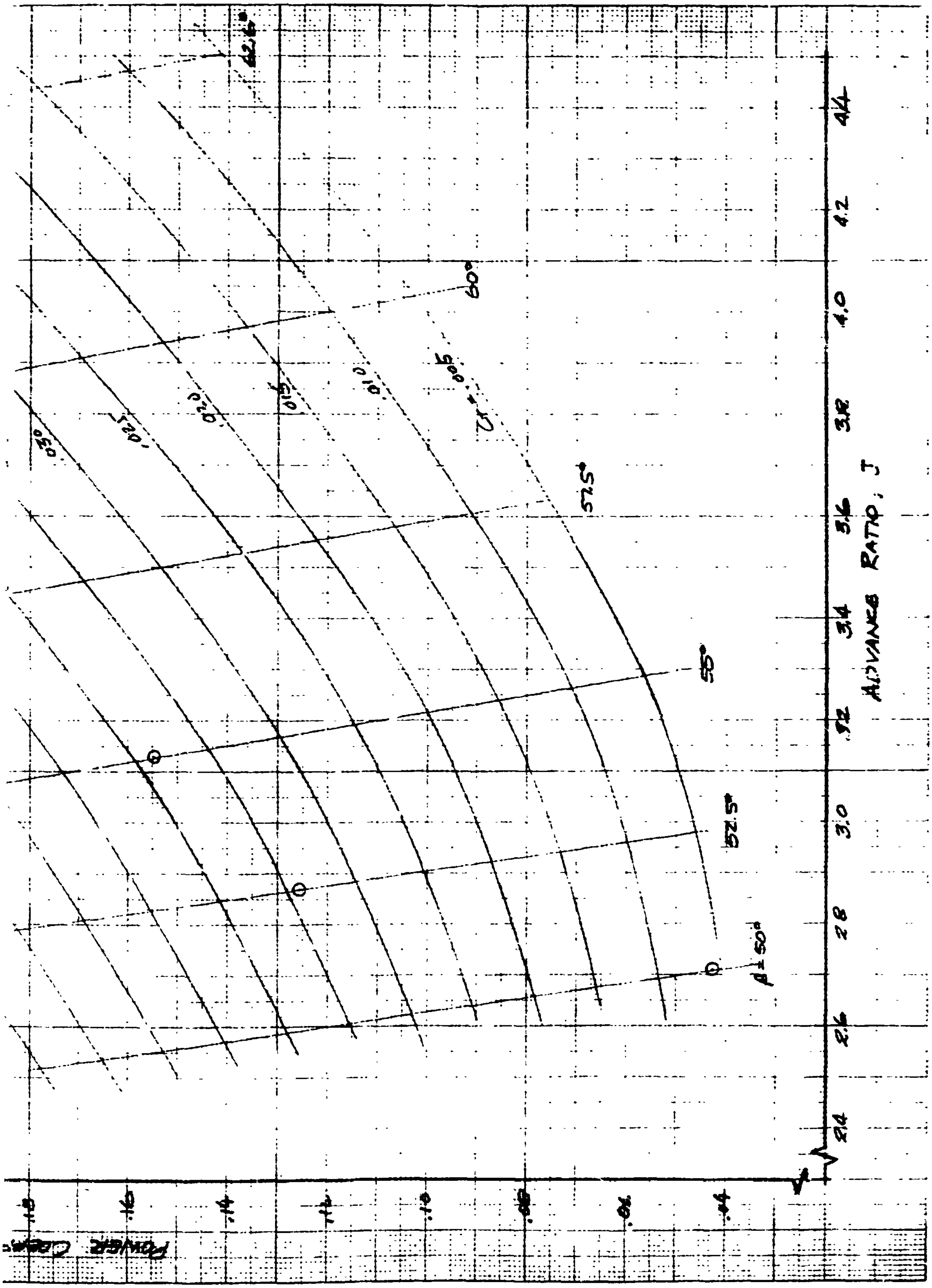
NUMBER D160-10021-1
REV LTR

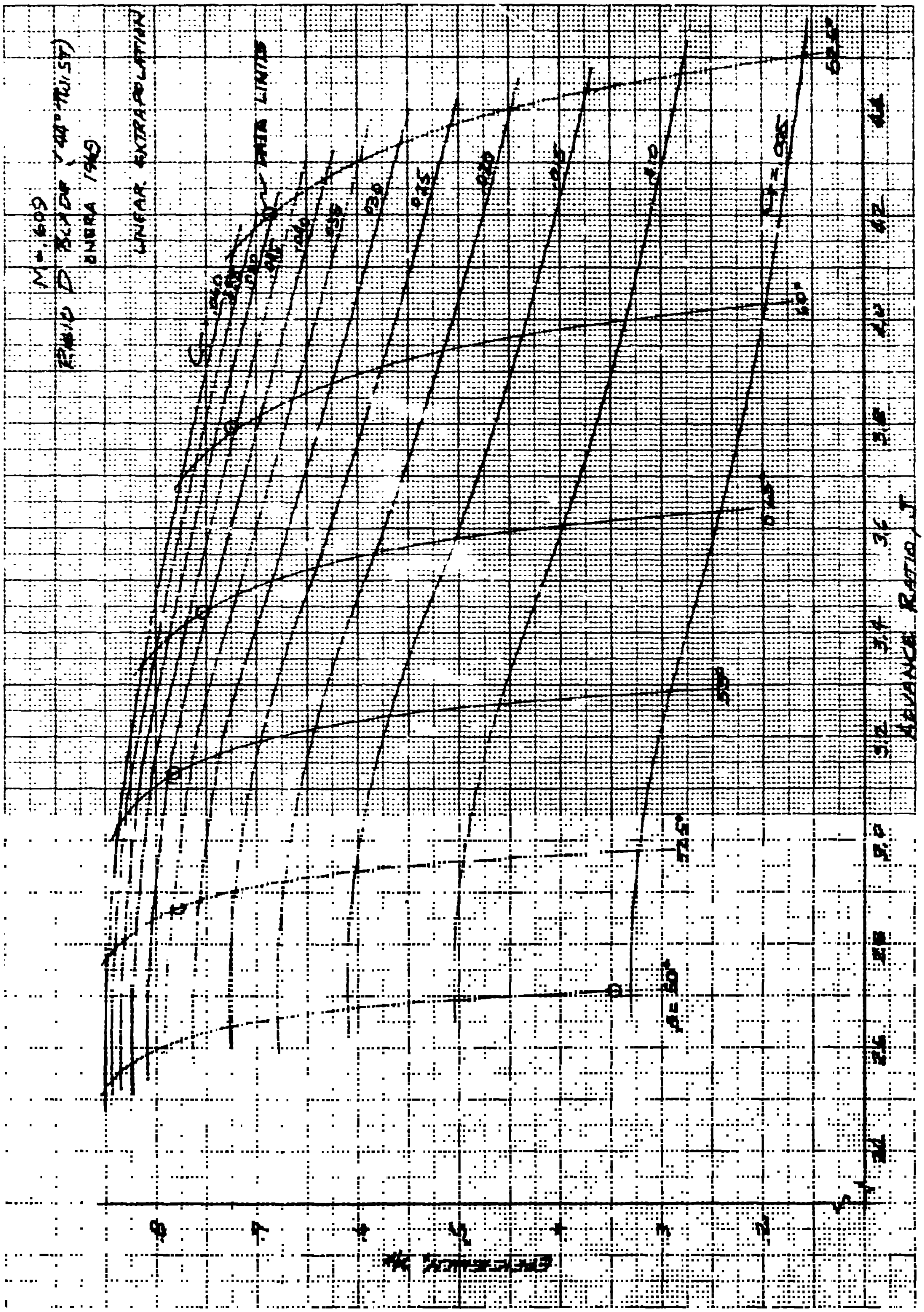


FOLDOUT FRAME 2

THE BOEING COMPANY

NUMBER D160-10021-1

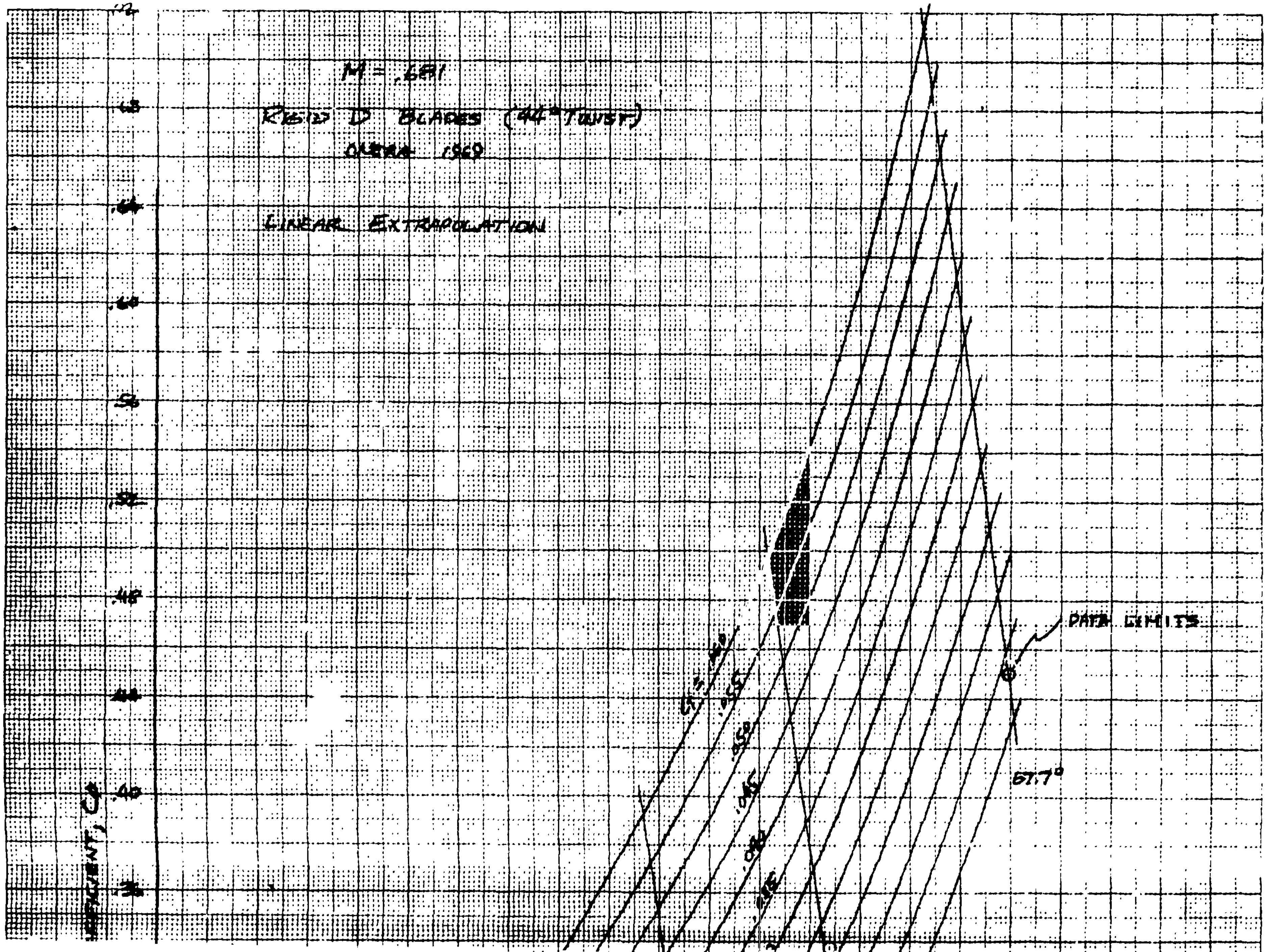
REV LTR



THE BOEING COMPANY

ND 340DR-MP DIETZGEN GRAPH PAPER
MILLIMETER

EUGENE DIETZGEN CO.



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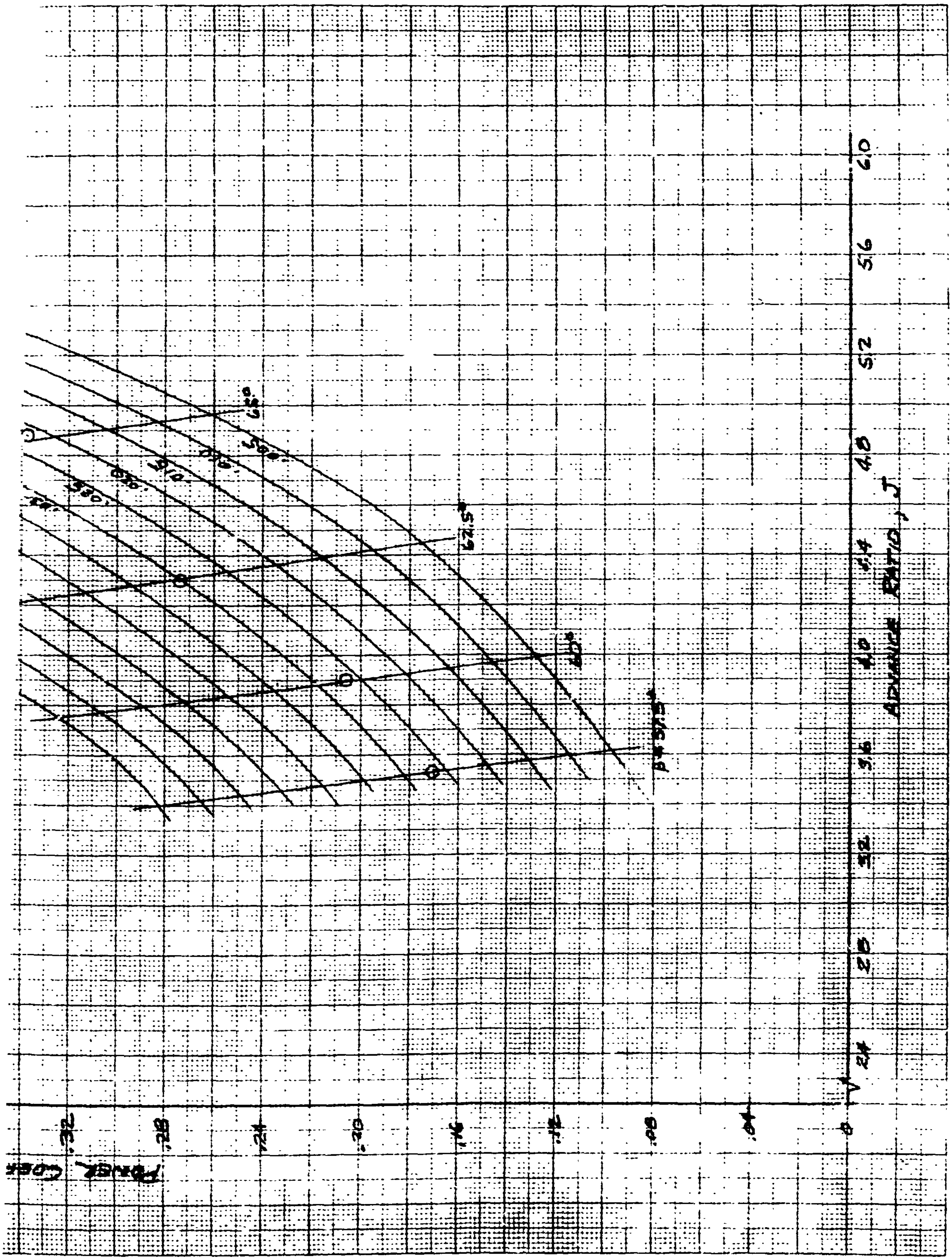
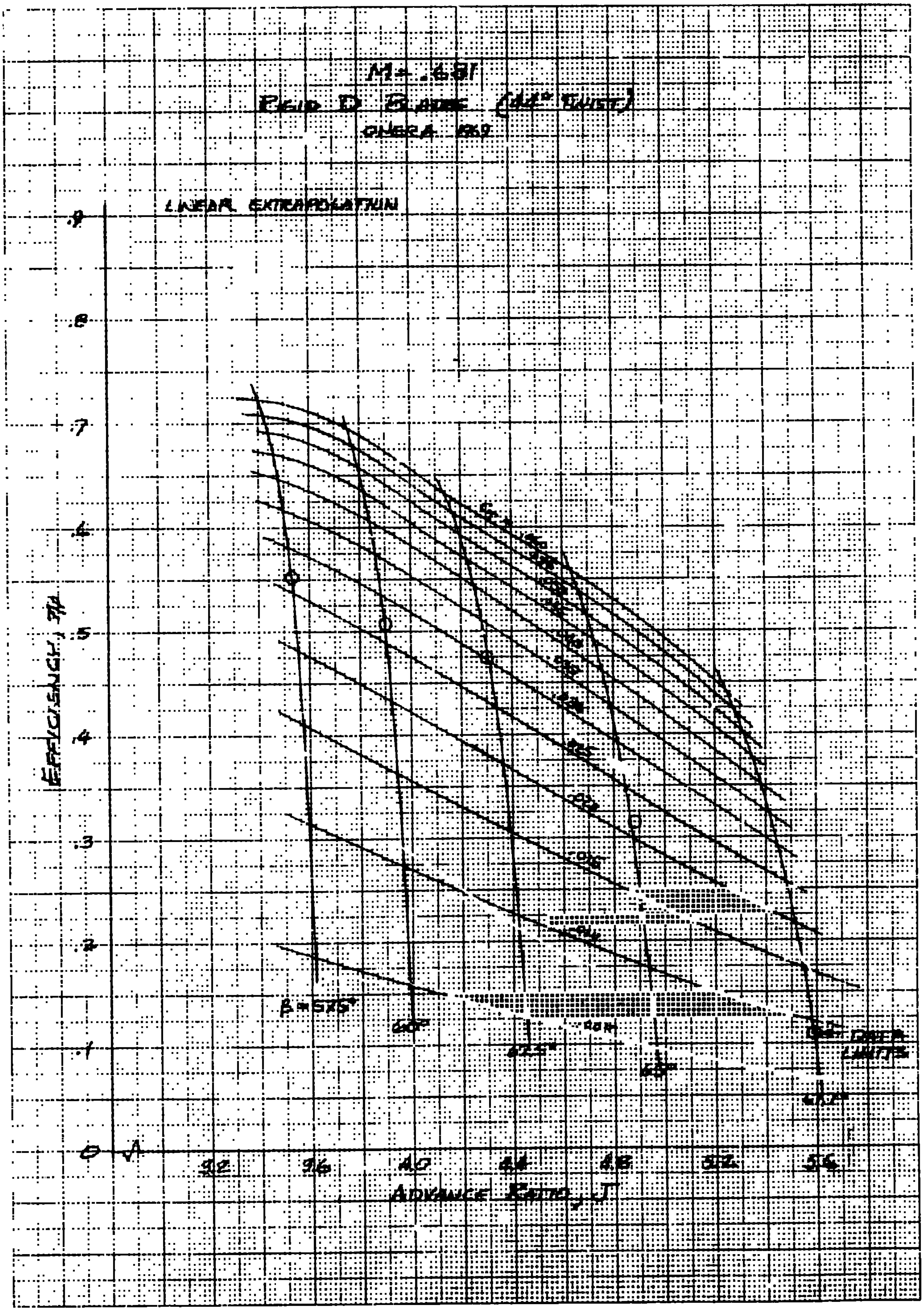

ADVANCE RATIO, J
POWER COEF
65°
62.5°
60°
57.5°
.32
.28
.24
.20
.16
.12
.08
.04
0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0


M = .681
LINEAR EXTRAPOLATION
EFFICIENCY, η
ADVANCE RATIO, J
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
3.2
3.6
4.0
4.4
4.8
5.2
5.6
β = 57.5°
60°
62.5°
65°
67°
DATA LIMITS

8.0 REFERENCES

BOEING DOCUMENTS

D160-10013-1 Investigation of the Performance of Low Disc Loading Tilt Rotors in Hovering and Cruise Flights - Volume I Analysis and Results

D160-10013-2 Volume 2 - Wind Tunnel Program Details

D160-10020-1 Pitch-Lag Flap Stability Test and Analytical Sensitivity Studies

D160-10016-1 Test Procedures for a Hover Performance Test on Rigid and Dynamically Scaled Rotor Performance Models

D160-10017-1 Test Procedures for a Cruise Performance Test on Rigid and Dynamic Rotor Performance Models

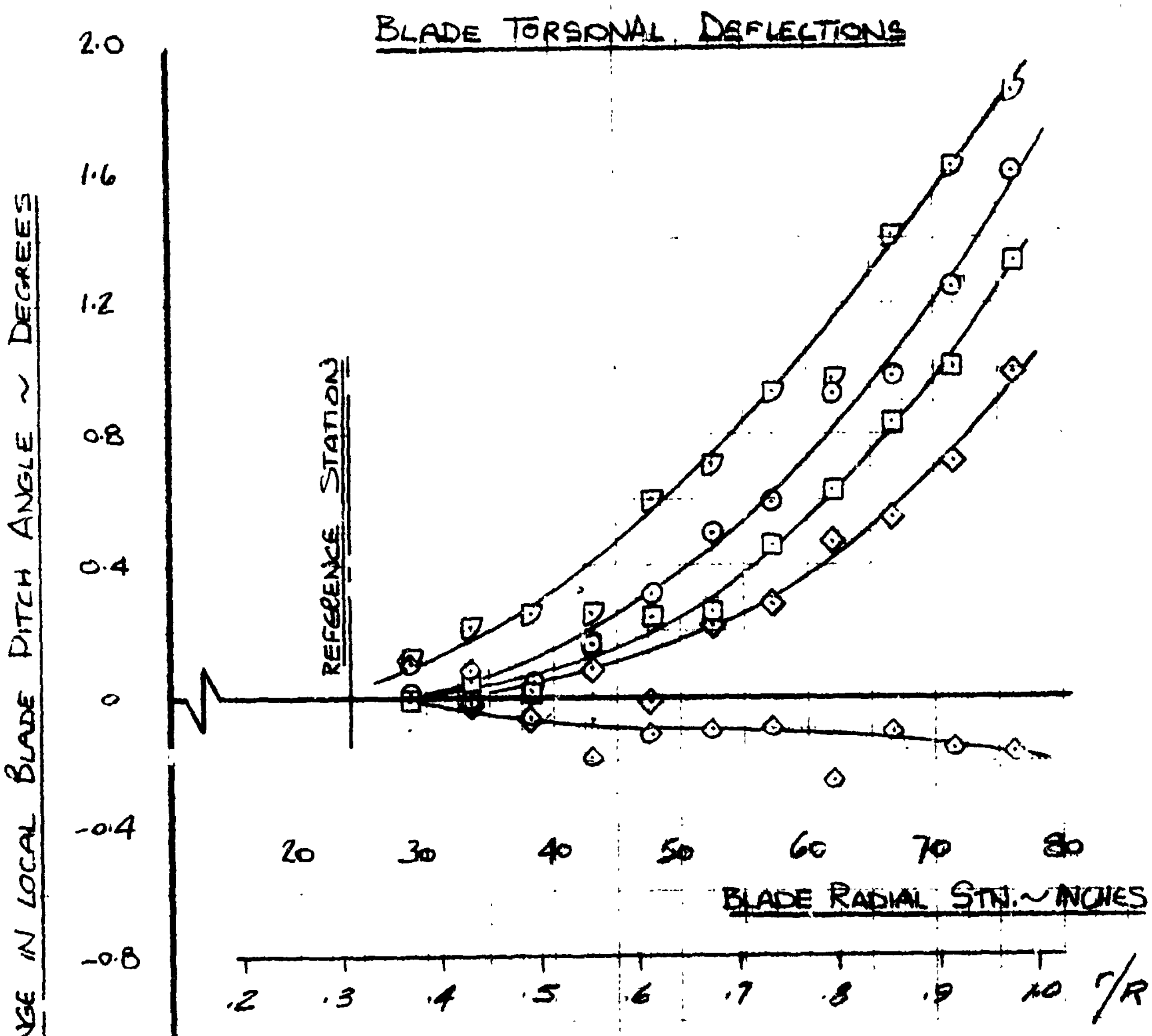
ONERA Document 1/1832 SN-Fasc. 1/2 NASA-ONERA Tests of Two 13/55 Scale Tilt Rotor Propellers in the SIMA Tunnel

AGARD Paper September 1972 A Summary of Wind-Tunnel Research on Tilt Rotors from Hover to Cruise Flight, W.L. Cook, NASA and P.Poisson-Quinton, ONERA

APPENDIX A EFFECT OF DYNAMIC DESIGN ON BLADE OPERATING TWIST

During the 1970 tests at ONERA photographic techniques were used to establish the effect of thrust loading on radial twist of the blades under operating conditions. The methods used to establish the change in twist of the E dynamic blades are described in D160-10013-1 and -2 and an AGARD paper by Mr. W. L. Cook and Mr. P. Poisson-Quinton. (The Aerodynamics of Rotary Wings, Marseille, France, September 1972).

Pages A-3 and A-4 are results of the tests using the photographic techniques. Page A-3 shows the radial variation of twist increasing as thrust and flight speed increases while Page A-4 indicates the effect of increased thrust on radial twist at a given flight condition.

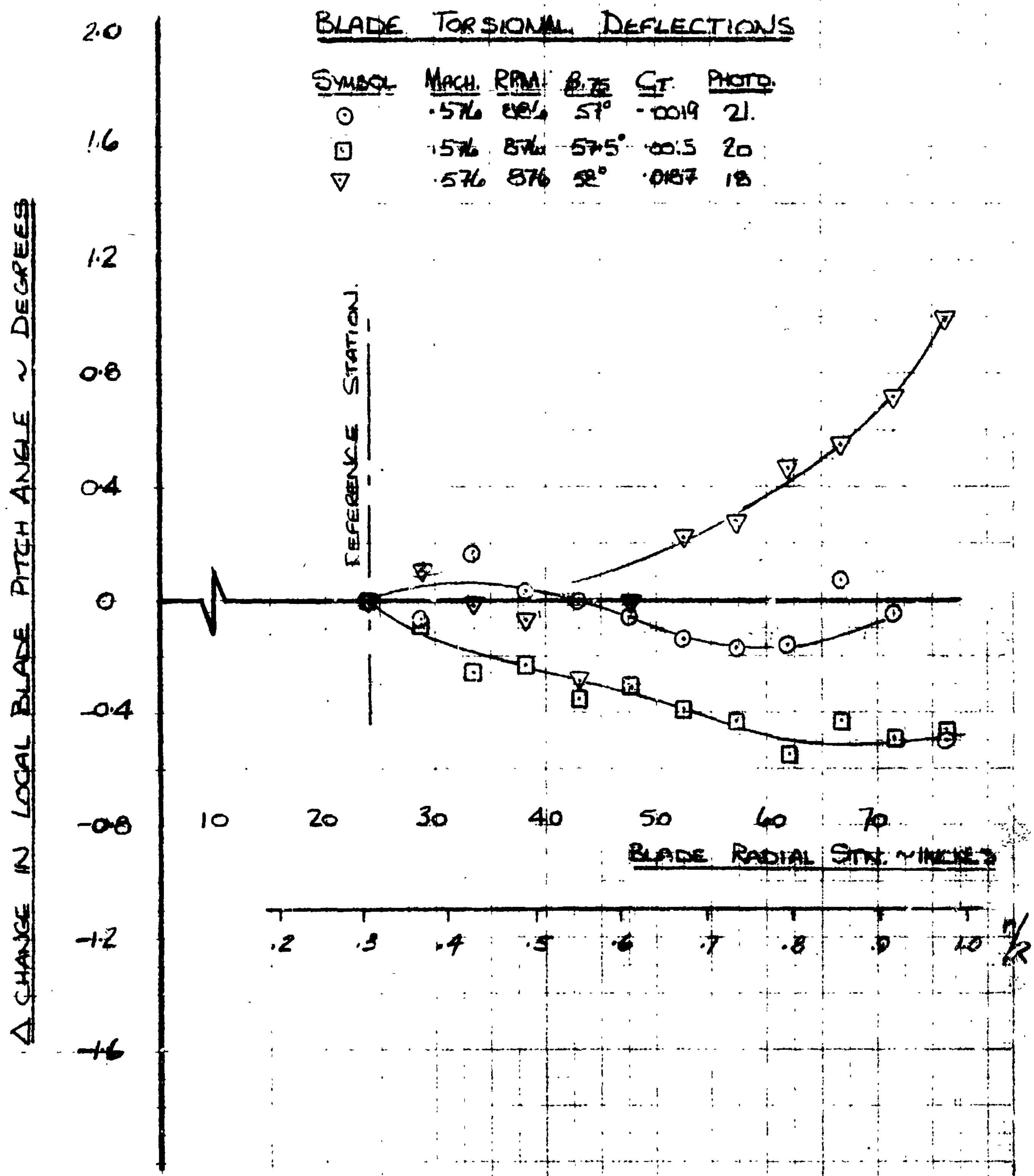


SYMBOL	MACH	RPM	$\theta_{.75}$	C_T	PHOTO.
⊙	.303	876	40°	.0136	7
⊡	.455	876	51.5°	.0164	13
◇	.576	876	58°	.0187	17
▽	.606	878	59.5°	.0347	28
◇	.606	872	59.0°	.0081	24

KJS 7.27.70

13' DIA. DYNAMICALLY SCALED ROTOR

NASA 2-5025-IV



KJS 7.27.70

13' DIA. DYNAMICALLY SCALED ROTOR

NASA 2-5025-IV